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Comprehensive Visualization of Interface Defeat-Based Ballistic Impact Damage in a Titanium Carbide (TiC) Ceramic Target Disk

by William H. Green, Joseph M. Wells,
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Comprehensive Visualization of Interface Defeat-Based Ballistic Impact Damage in a Titanium Carbide (TiC) Ceramic Target Disk

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Abstract

This study was initiated to demonstrate the feasibility of applying the state-of-the-art nondestructive testing methodology known as x-ray computed tomography (CT) to a ballistic damage assessment. Specifically desired is the capture, digitization, and display, in both two-dimensional (2-D) and three-dimensional (3-D) formats, of the actual mesocracking damage created in bulk ceramic targets following an interface defeat or dwell ballistic impact experiment. Dwell involves the delay, and interface defeat involves the prevention, of penetration by a long rod penetrator into the ceramic. In each mechanism, the penetrator material contacting the ceramic front face flows laterally. These mechanisms occur at or near the impacted front surface of a highly confined armor ceramic material and may result in considerable subsurface or interior damage. This study also reports on the development of a new capability to graphically represent the full assemblage of networked interior mesocracks by an isolated 3-D point cloud or wireform model which aids significantly in the visualization and understanding of the entire mesocracking damage network. Practical limits of image spatial resolution with this technique (≈400 μm for large volume samples) preclude the nondestructive characterization of the detailed microcracking damage at this time.

Acknowledgments

The authors would like to acknowledge the most professional support of George Hauver for sharing both his TiC armor ceramic disk sample and his insight and knowledge of interface defeat. Also, we would like to sincerely thank Drs. J. LaSalvia, A. Wereszczak, K. Doherty, J. Beatty, and A. Dietrich for their comments and efforts in reviewing this manuscript.

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1. Introduction

Bless et al. (1992) achieved interface defeat with a titanium diboride (TiB_2) ceramic tile with a loss of ceramic to only a depth of 5.5 mm. Hauver et al. (1994) subsequently demonstrated the phenomenon of interface defeat using a highly confined target disk with several ceramics, including silicon carbide (SiC), titanium carbide (TiC), TiB_2, and tungsten carbide (WC). Lundberg et al. (2000) and LaSalvia et al. (2000) have recently reported on the transition between interface defeat and penetration. While the actual penetration of the projectile into the ceramic is very limited with the occurrence of interface defeat, there is, nevertheless, considerable subsurface internal damage in the target ceramic ahead of the ceramic boundary. This damage consists mainly of a comminuted zone of pulverized ceramic containing both microcracks and voids and, frequently, a larger network of considerable mesocracking. The mesocracks are of conical, radial, and lateral (laminar) orientation and are generally between about 10^2–10^3 µm in width. Similar subsurface cracking damage has also been described by Shockey et al. (1990) using destructive sectioning.

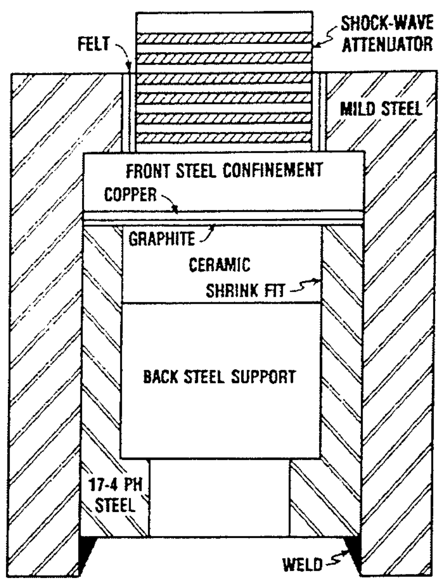
1.1 Intrinsic Mesocracking Damage

Ballistic evaluations frequently concentrate on in-situ flash x-ray diagnostics and post-mortem penetration (e.g., DOP, V_{50}, etc.) measurements, all of which are extrinsic to the internal damage of the target material. Characterization of the internal impact damage in ceramic targets is normally limited to impact surface fractography and random through-thickness sectioning for polishing and ceramographic examination. The latter is seldom done in sufficient amount to capture a detailed understanding of the intricate and complex nature of the intrinsic three-dimensional (3-D) mesocracking portion of the ballistic damage.

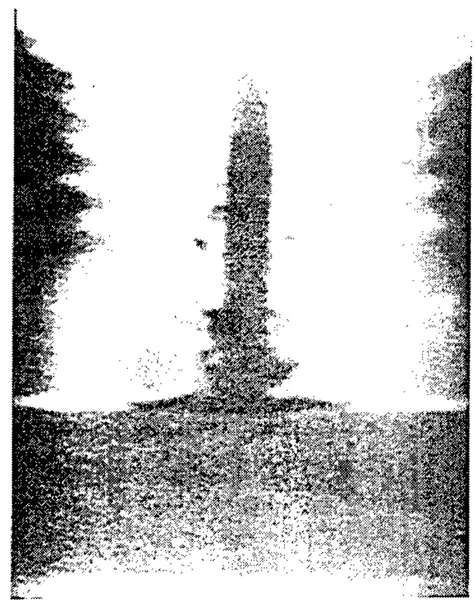
Such mesocracks seriously reduce the capability of the ceramic material in resisting penetration from subsequent impacts (Hauver et al. to be published). Indeed without lateral confinement, the ceramic with developing mesocracks would shatter under a single ballistic impact and would not achieve the condition of interface defeat at all. If the mesocracking can be reduced, modified, or eliminated, the structural integrity of the ceramic and its intrinsic resistance to penetration can be improved substantially. First, however, one needs to be able to accurately observe and measure the nature and extent of this mesocracking damage nondestructively. Thus, our objective was to develop a methodology that allows the detection, measurement, and the 3-D visualization of the resulting mesocracking damage. Destructive sectioning for microscopic examination of either the micro- or mesocracked areas also can be utilized to further evaluate the intrinsic ceramic damage. It was felt that the availability of this tool would prove useful in the selection of destructive sectioning locations and in the evaluation of the ballistic confinement design as well. This tool may then lead to an improved understanding of the impact damage that limits ballistic performance. Subsequently, it may also assist in the optimization of the intrinsic capability of the target ceramic material and their confinement designs to increase dwell (LaSalvia et al. 2000), resist penetration and, ultimately, to better fully defeat the impacting penetrator.

1.2 Ballistic Testing Approach

The resistance of a ceramic target material to ballistic penetration is known to be influenced by the design configuration of the target assembly, the severity of the projectile threat, and the structure/properties of the confined ceramic target material (Figure 1).



(a)



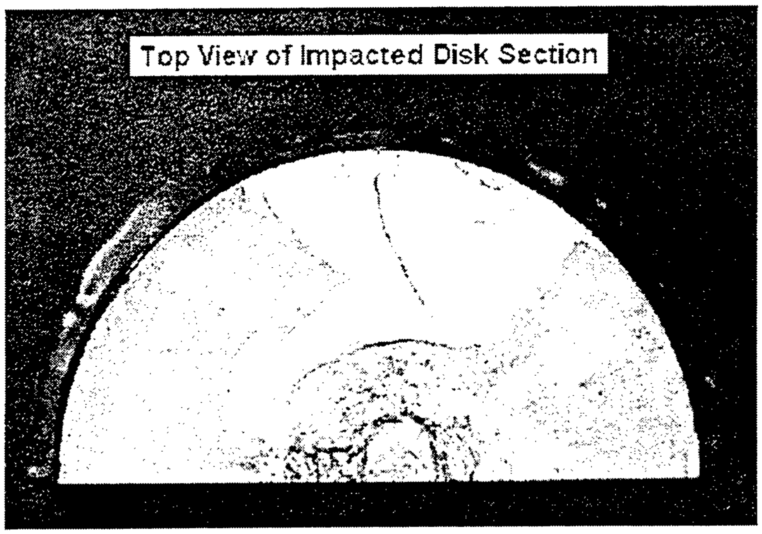
(b)

Figure 1. Depictions of (a) schematic of heavy constraint ballistic test fixture and (b) flash x-ray of the penetrator experiencing interface defeat at the front surface of the TiC disk. Not to scale (Hauver et al. to be published).

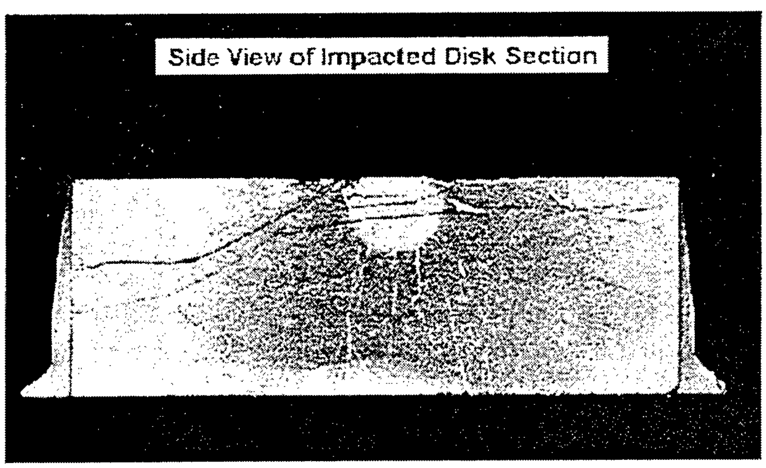
The heavy constraint apparatus used by Hauver et al. (1994) for confining the TiC ceramic sample disk during the ballistic impact testing is shown schematically in Figure 1(a). A high-speed flash radiograph showing the interface defeat of the impacting penetrator with lateral flow at the front surface of the TiC disk is shown in Figure 1(b). The penetrator was a 90% W alloy short rod with a length-to-diameter ratio (L/D) = 20, and impacted the target at a contact velocity of about 1,600 m/s.

1.3 TiC Sample Description

The TiC ceramic sample utilized in this study was provided by George E. Hauver and is one-half of a 72-mm-diameter × 25-mm-thick ceramic target disk section (Figures 2[a] and [b]). A higher magnification view of the sample cross section containing the comminuted zone and the mesocracking is more clearly shown in Figure 3.



a. Macrophotograph of TiC ceramic half-disk, 72-mm in diameter, showing front (interface defeat) impact surface.



b. Macrophotograph of TiC ceramic half-disk, 25 mm thick, showing comminuted microdamaged zone (light circular area) and mesocracking through the thickness of cross section.

Figure 2. Macrophotograph of TiC ceramic half-disk showing impact surface and damaged zone.

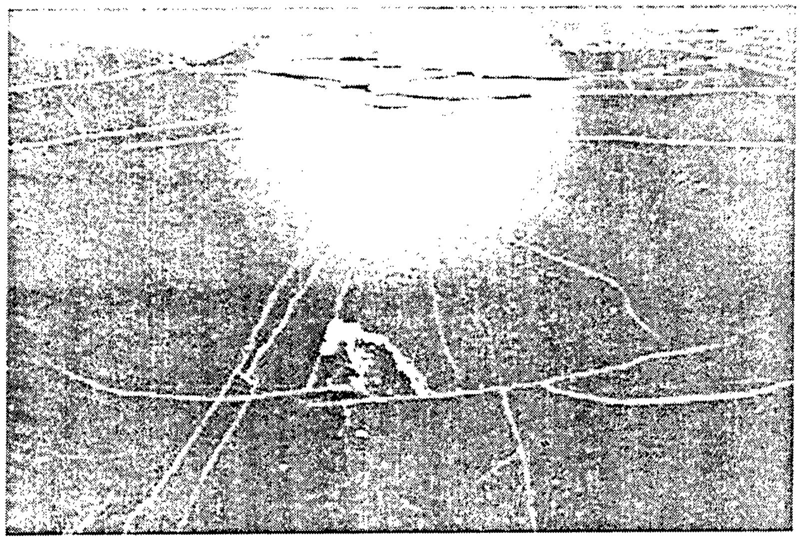


Figure 3. Closer view of the comminuted zone (light circular area) and the prominent mesocracking in TiC disk (LaSalvia et al. 2000).

2. X-ray Computed Tomography (CT) Method

2.1 Principles and Technique

Figure 4 schematically shows the rotate-only (RO) x-ray CT technique. The x-ray source and detector remain stationary. The object remains stationary relative to the turntable. The collimated horizontal fan beam "scans" a slice of the object, as the turntable rotates 360°. The height above the turntable and thickness of the slice are known. A set of attenuation line integrals is generated from the scan. The line integrals can be conceptually grouped into subsets referred to as "views." Each view corresponds to a set of ray paths through the object from a particular direction. The views are also referred to as "projections" or "profiles," while each individual datum within a given projection is referred to as a "sample," or often just a "data point."

A state-of-the-art scanner routinely collects millions of measurements per scan, each one accurately quantified and precisely referenced to a specific line of sight through the object of interest. The views from the scan are passed to the reconstruction algorithm for processing (Stanley 1985). The CT reconstruction process yields a two-dimensional (2-D) array of numbers corresponding to the cross section of the object. This 2-D array of numbers (i.e., densitometric gray levels) is the CT image.

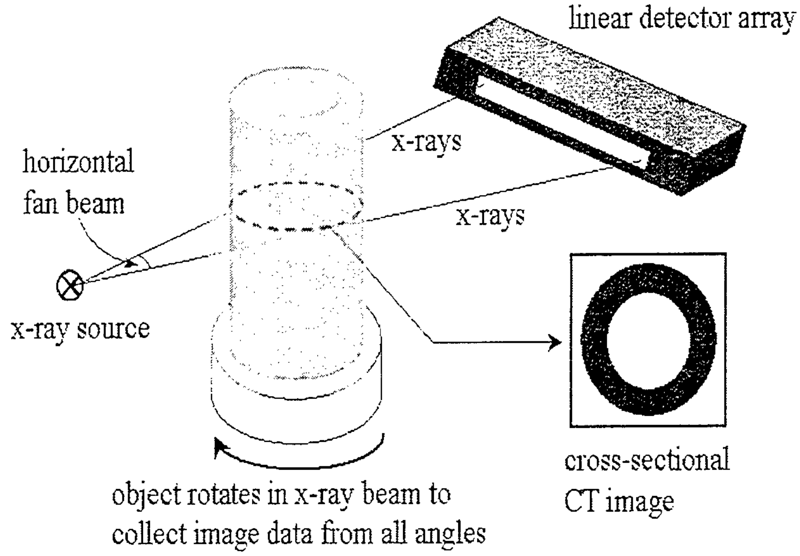


Figure 4. Schematic of RO CT scan technique.

2.2 3-D Volume Reconstruction

The excellent dimensional accuracy and the digital nature of CT images allow the accurate volume reconstruction of multiple adjacent slices. The slices are "stacked" to provide 3-D information throughout the entire object or a section of the object. Two ways of visualizing volumetric data are multiplanar reconstruction (MPR) and 3-D reconstruction. MPR (visualization) displays top, front, side, and oblique slices through the object. The orientation of the top slice is parallel to the cross-sectional image plane. The front slice is orthogonal to the top slice. The side slice is orthogonal to both the top and front slices. The oblique slice can be placed on any one of the other three slices. The MPR display is similar to an engineering drawing. However, each view (i.e., top, front, side, and oblique) is a slice with finite thickness through the object, not a 2-D projection. The top, front, and side slices can be moved anywhere in the reconstructed volume. The oblique slice can be rotated through 360°.

The volumetric data is displayed as a 3-D solid object in 3-D reconstruction, and the orientation of the solid in space can be changed to facilitate different views. The solid can also be "virtually" sectioned by only displaying part of the reconstructed volume, which creates a "virtual" cutting plane on the solid showing the x-ray density values on that plane. This plane may be orthogonal to the cross-sectional image plane. In effect, virtual sectioning shows the exposed surface as it would look if the object were actually destructively sectioned along that plane.

2.3 3-D Point Cloud Generation

As previously stated, a CT image is a 2-D array of densitometric gray levels (i.e., CT densities). For example, a 12-bit image would have 4,096 levels of gray from black to white, with darker (blacker) normally indicating less x-ray attenuation and lighter (whiter) indicating more attenuation. The field of image processing is much too large to discuss in detail here, but it is sufficient to state that different materials in an image can be visually delineated to a high degree using various image processing techniques based upon their attenuation characteristics. In fact, black (gray level = 0) and white (gray level = 4,095) images can be generated using appropriate contrast enhancement. This is normally done to accurately define material (white) boundaries. Any number of black and white (i.e., binary) images can be vertically stacked to generate a 3-D point cloud, in which the set of points in space defines the internal and external surfaces of the object. Furthermore, a point cloud can be "polygonized" or made into a wireform model.

3. Experimental Technique

3.1 CT Equipment

The TiC half-disk was examined using a customized ACTIS 600/420 CT system designed and constructed by Bio-Imaging Research (BIR), Inc. and installed at the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground (APG), MD. It has a 420 keV x-ray tube with two focal spot sizes and a 160 keV microfocus x-ray tube with four focal spot sizes, the smallest being 10 μ. It also has a linear detector array (LDA) and an image intensifier (II) with a zoom lens and a charged-coupled device camera. CT scanning can be done using the LDA or the II. The system can scan in RO and offset-RO mode using either source and the LDA or the II, and in translate-rotate (TR) mode using the LDA and either source. It can also perform digital radiography (DR) scans using the LDA or II.

3.2 CT Technique and Image Resolution

The entire height of the TiC sample was scanned perpendicular to the impact face in TR mode with the sectioned surface resting on the turntable. The source-to-object distance (SOD) and source-to-image distance (SID), were 662.8 mm and 930.0 mm, respectively. The slice thickness and increment were 0.50 mm and 0.20 mm, respectively, resulting in overlapping scans. Overlapping scans generally improve MPR and 3-D solid images because they result in better quality attenuation data (i.e., better photon statistics) in the overlapping regions. Each slice was reconstructed to a 1,024 × 1,024 image matrix using 1,238 views. Scan time was about 25 min/slice with 183 slices required to scan the entire sample. The scan configuration used the 420 keV tube with the LDA. The tube energy and current used were 350 keV and 2.5 mA, respectively, and the focal spot was 0.8 mm.

A second set of CT scans was also conducted parallel to the impact face in RO mode with the back face resting on the turntable. The SOD and SID were 747.6 mm and 950.0 mm, respectively. The slice thickness and increment were both 0.50 mm, resulting in contiguous scans. The scan configuration used the 420 keV tube with the LDA. The tube energy and current used were 415 keV and 2.0 mA, respectively, and the focal spot was 0.8 mm.

Table 1 lists approximate image resolution achieved for the different modes of image visualization.

Table 1. Summary of visualization modes and image spatial resolution for TiC mesocracking data.

Visualization Mode	View Description	Image Spatial Resolution
2-D CT Slice	Traditional cross section plane orthogonal to vertical axis	≈ 400 μm
MPR Pseudo 3-D	Arbitrary multiplanar slices	≈ 400 μm (500 μm in z direction)
3-D Solid (with or without cut sections)	Oblique view showing cracks within base TiC material	≈ 400 μm (500 μm in z direction)
3-D Point Cloud (polygon/wireform model)	3-D view of crack network only with base material removed	≈ 400 μm (500 μm in z direction)[a]

[a] Assumes point cloud is not significantly under sampled.

4. TiC Results

4.1 Digital Radiography and 2-D CT Slice

A digital radiograph in the through-thickness direction and three CT slices are shown in Figure 5. The vertical position of each slice is shown on the DR by dashed lines. The purely vertical streaking in the DR and the moiré fringe

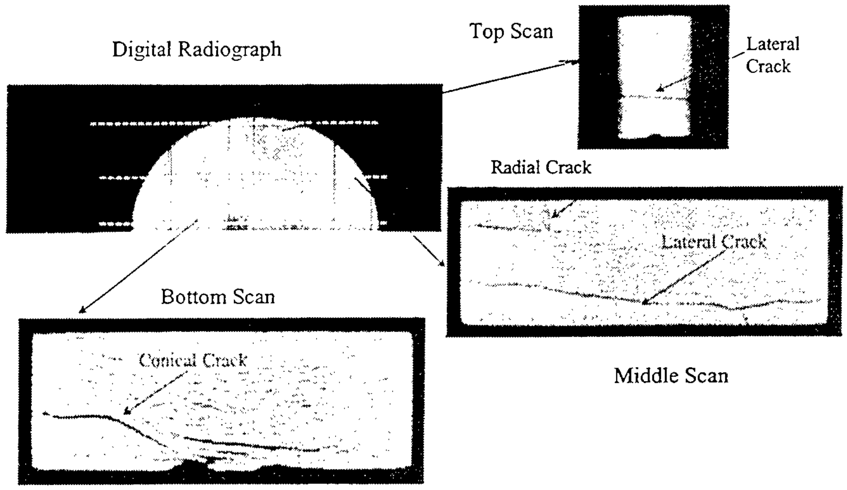


Figure 5. DR and 2-D CT slices in TiC sample.

pattern in the bottom CT slices are image artifacts. Mesocracking damage is readily apparent in both the DR and CT slices, even with the artifacts. The impact face is at the bottom of each slice.

4.2 MPR Visualization

Figure 6 is a MPR visualization of the entire sample with the top slice view parallel to the image plane. The top slice view is 18.18 mm from the sectioned surface; all the views show crack damage. The front slice and side slice views show the distribution of damage perpendicular to and in the through-thickness direction, respectively, for those slices. The oblique slice view shows an area of concentrated damage, which is comminuted ceramic material, in the immediate vicinity of the sectioned surface and additional cracking damage shaped roughly like a ring between the top and the sectioned surface. The oblique angle is 5° from the horizontal in the top slice view.

Figures 7(a)–(c) are top slice and front slice views with increasing distance into the sample interior moving away from the impact surface. The mesocracking damage in slices perpendicular to the through-thickness direction changes with distance into the sample interior.

A radial mesocrack is seen at the 5 o'clock position in the front slice views in Figures 7(a) and (b). Figures 8(a)–(c) are top slice and side slice views with different side slice locations. The side slice locations in the figures are 26.89 mm, 15.61 mm, and 5.64 mm to the left of the axis of the sample, respectively. The series of side slice views shows how both conical and lateral cracking damage in the thickness direction change with distance from the line of impact.

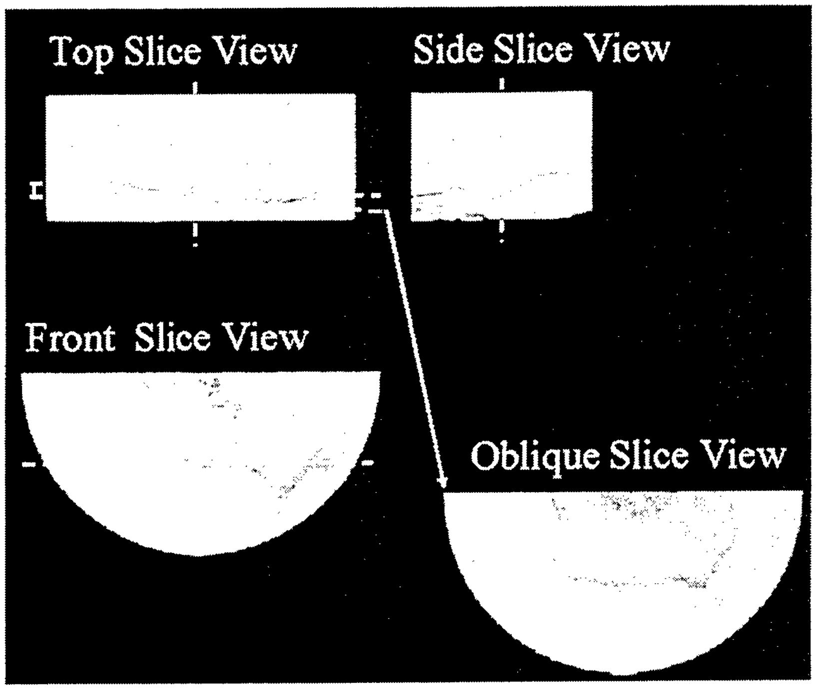
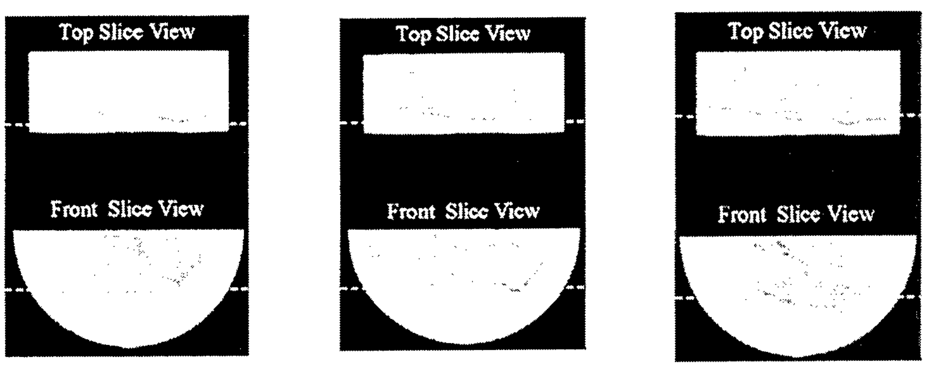


Figure 6. MPR visualization of TiC sample.

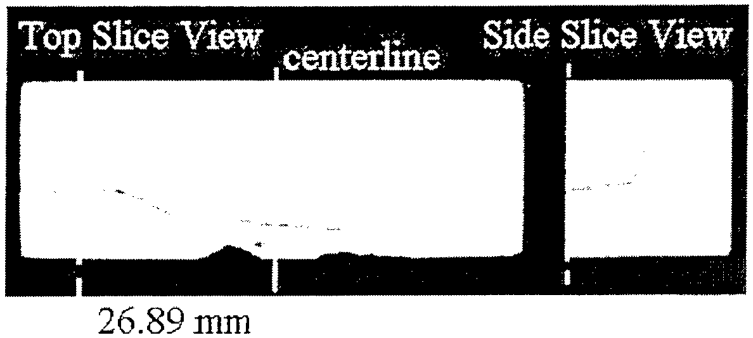


(a) 2.98 mm from impact face (b) 3.98 mm from impact face (c) 5.97 mm from impact face

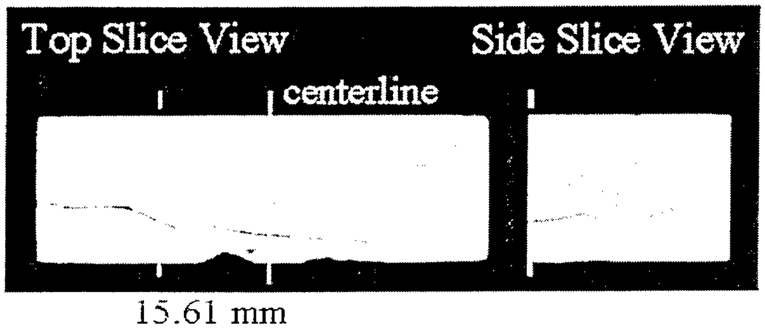
Figure 7. Top and front slice views with different front slice distances from impact face into TiC sample interior.

4.3 3-D Solid Visualization

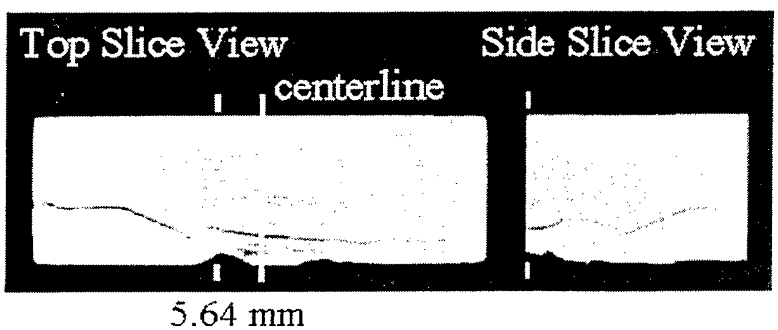
Figures 9(a)–(c) are 3-D solid visualizations showing different virtual surfaces. Figure 9(a) shows the entire sample and accurately reflects the damaged condition of the impact face. Figure 9(b) shows the sample with approximately one-half of it virtually cut off; conical and lateral cracking damage is readily apparent. Figure 9(c) shows the sample with two virtual cuts, the first



(a) 26.89 mm from axis



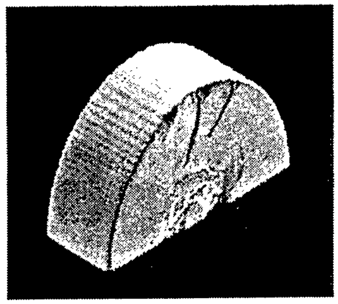
(b) 15.61 mm from axis



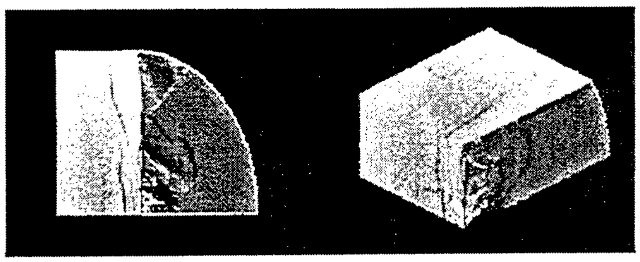
(c) 5.64 mm from axis

Figure 8. Top slice and side slice views with different side slice distances from axis (centerline) showing conical and laminar mesocracking.

being the same as in Figure 9(b). The sectioned surfaces appear as if the sample was actually cut at those surfaces. This is an effective way to visualize damage on sectioned planes in particular locations/directions while maintaining its registration to the entire original sample. The sample material is still represented in opaque bulk form and thus blocks access to contiguous damage features on adjacent slices not currently in view. A more comprehensive set of 3-D solid visualizations is presented in Appendix A.



(a) Original sample



(b) One-half of the sample (c) Two-cut section

Figure 9. 3-D solid visualizations of TiC sample.

4.4 3-D Point Cloud and Wireform Visualization

It is difficult, therefore, to conceptualize the entire network of the mesocracking from these virtual surface views. It would be very tedious to look at hundreds or even thousands of these 2-D, MPR, or 3-D solid 3-D views to try to "get a complete picture" of the internal mesocracking. However, a 3-D point cloud provides the desired kind of information about the cracking pattern. The first step in obtaining the point cloud is to perform the required image processing to "clean up" undesirable image features or artifacts. DUP Technologies plug-in routines contained in the Adobe PhotoDeluxe Business Software were used to enhance the appearance of the CT scans. These routines do not add further detail beyond that present in the original scans. They do, however, allow the enhancement of sharpness in the scans by defining edges, reducing the dotted, grainy appearance of the scans, and removing moire patterns.

The moire fringe pattern removal routine also appeared to have the effect of removing very thin, faint crack damage. Figure 10 shows a CT slice near the sectioned surface of the sample to which this technique has been applied. The fringe pattern has been mostly removed with only a few vestiges of it remaining in and around the center of the image.

Figure 10. A preprocessed image.

The next step is to determine the best gray level to use to threshold and binarize (i.e., show only two gray levels or black and white) the images. This is done by "line profiling" the feature or features of interest in the image, as shown in Figure 11. Normally the full-width-half-maximum value, which is the gray level halfway between the minimum and maximums of the profile, is used. The result of binarizing the image in Figure 10, based on the profile in Figure 11, is shown in Figure 12 in which the crack damage along with some comminuted damage, are black and undamaged material is white.

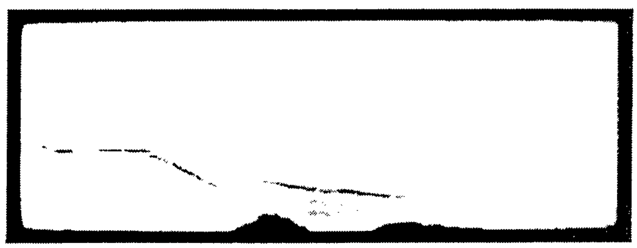


Figure 11. Gray level line profile through a crack.

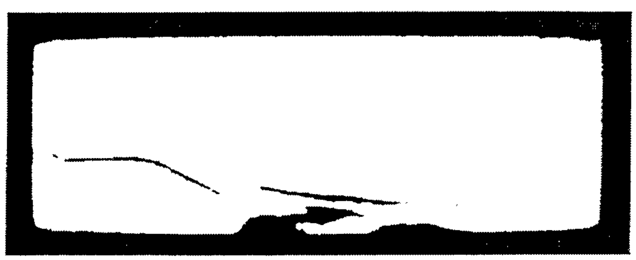


Figure 12. Preprocessed, thresholded, and binarized image.

Any number of binary images like the one shown in Figure 12 can be volumetrically combined to generate a 3-D point cloud describing "boundaries" of the cracking damage and comminuted ceramic material. In fact, the 51 binary images created from the RO CT slices throughout the volume of the sample were combined to generate a 3-D point cloud in order to describe the mesocracking and comminuted damage as they are located in the sample.

A systematic sampling technique was applied to decrease the amount of data and make the point cloud more visually informative, since the point cloud contained more points than were necessary for data analysis. Figure 13 shows the resulting point cloud, in which the x-direction is to the left and the z-direction is rotated 20° counterclockwise (i.e., out of the page) from vertical about the x-axis. The z-direction relative to the sample is from the back face to the impact face. Therefore, the point cloud is oriented such that the semicircular impact face, which is physically at the top of the image, is being viewed obliquely. Also, the sectioned edge along the diameter on the back face is physically at the bottom of the image. BIR ACTIS software was used to perform the line profiling, create binary images, and generate point cloud data. SURFACER software by SDRC/Imageware, Inc. was used to visualize the point cloud data.

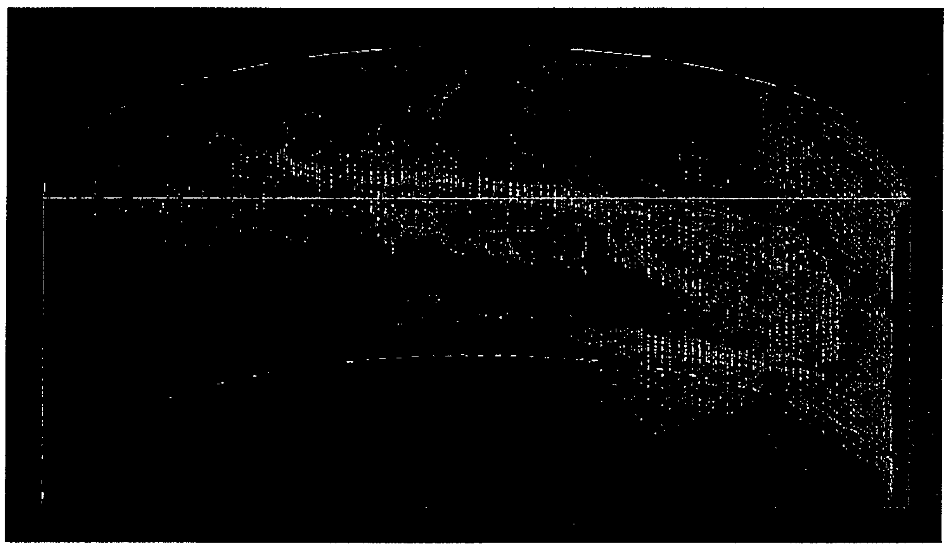


Figure 13. A 3-D point cloud (wireform) visualization of the entire mesocracking network.

While Figure 13 is a much more comprehensive image than those previously shown, it is the first static visualization of the *entire* TiC mesocracking damage pattern. This damage pattern is observed to be very asymmetrical with the largest damage volume (laminar and radial cracks) on the right hand side of this figure. In the upper center of the figure, an intermixing of mainly conical and laminar cracking is observed. Most of this cracking damage appears to be contiguous and perhaps interconnected, although distinct isolated cracking areas are observed in the lower center. A dynamic multi-axial rotating 3-D computer image reveals these features in a more comprehensible fashion, as shown in Appendix B.

5. Summary and Conclusions

We have demonstrated four different nondestructive methods (i.e., 2-D CT, MPR pseudo 3-D, 3-D solid, and 3-D point cloud or wireform) of visualization of the mesoscale cracking in a TiC ceramic target sample resulting from an interface defeat ballistic impact experiment. All four methods described herein allow increased visualization of the interior mesocracking at known depths within the sample. Normal digital x-rays provide no such flexibility of depth into the interior specimen thickness. The details of the complex and interwoven cracking patterns of the different constitutive cracking types are revealed with the point cloud image in a still complex yet more comprehensible perspective. The 3-D geometry and depth profile of such internal mesocracking damage has now become more easily visualized. Utilizing 3-D solid rotation software, one can further examine the point cloud mesocracking image from multiple orientations. While the image spatial resolution is insufficient to examine the microcracking damage directly, the described visualization techniques can assist in the selection of judicious locations for further destructive sectioning and subsequent high magnification ceramographic analysis. This microcracking has been considered recently by LaSalvia et al. (2000) through destructive examination and mechanistic modeling.

We have demonstrated also that the x-ray CT scanning technique is a viable and potentially useful tool in the detection and assessment of ballistic impact damage in brittle ceramic target materials. This tool may also be applied to assess damage resulting from configuration design changes as well as material modifications. While not yet able to separate the ensemble of each of the separate constituent cracking damage types, one can appreciate the convolution of their individual ensembles in the assymetrical overall mesocracking damage network. Further work is needed to develop the capability of deconvoluting the point cloud or wireform image into the constituent mesocracking types for semi-quantitative 3-D analysis. Such a deconvolution methodology would permit the individual cracking types to be independently assessed both geometrically as well as semi-quantitatively.

Finally, Grace (1997; 2000) has suggested that a combination of stress analysis and damage observations may point to possible ceramic failure mechanisms. It is thus desirable to eventually superimpose a computational volumetric stress analysis map over the volumetric mesocracking map (wireform) in order to examine damage correlations and to make comparisons to the explicit geometrical ballistic damage predictions of mechanistic mesodamage models as they become available.

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Appendix A. Virtual Sectioning of Titanium Carbide (TiC) Disk Using Three-Dimensional (3-D) Solid Visualization

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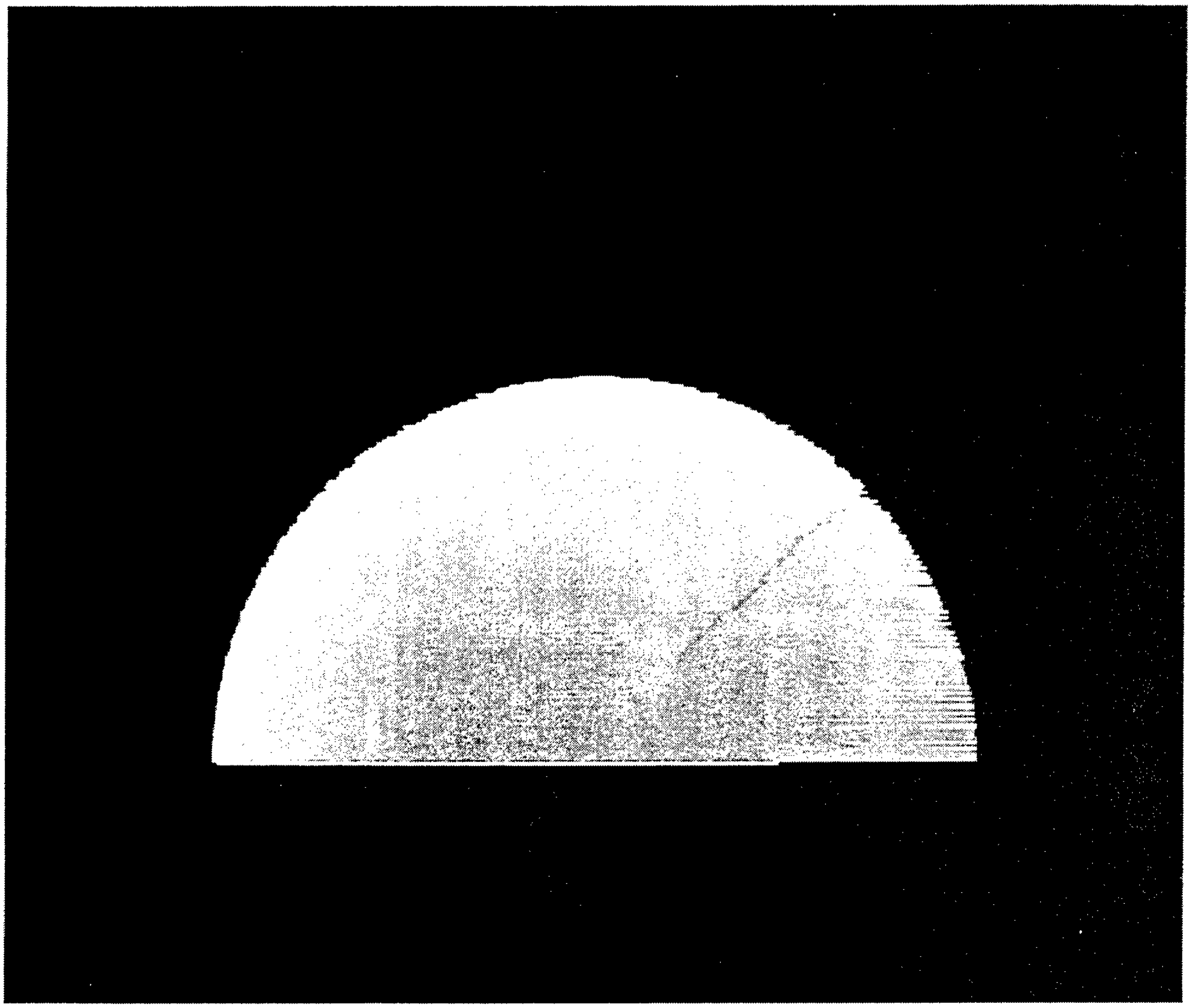

Figure A-1. 0.89 mm from bottom of disk with 65° rotation about X-axis.

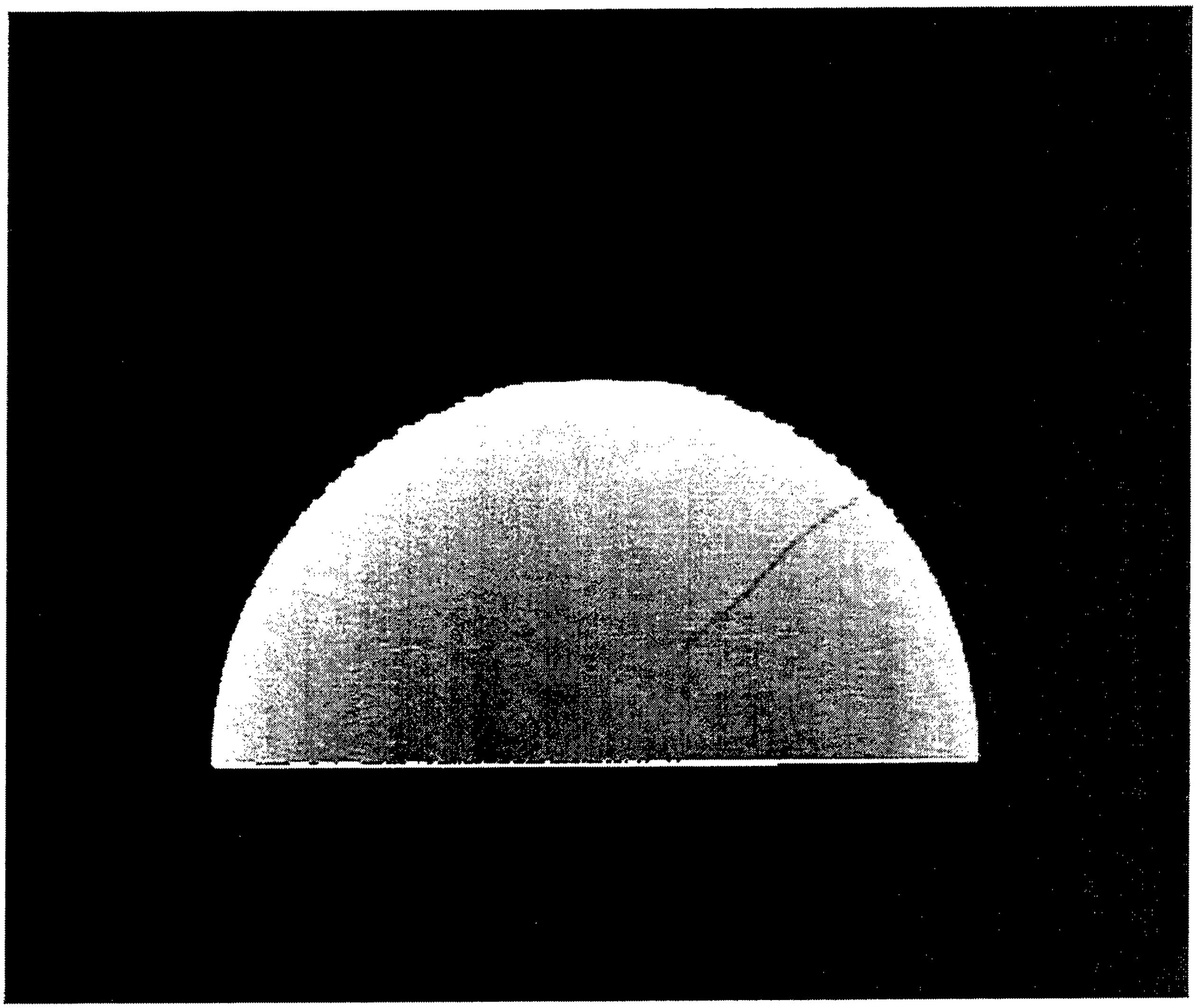

Figure A-2. 1.58 mm from bottom of disk with 65° rotation about X-axis.

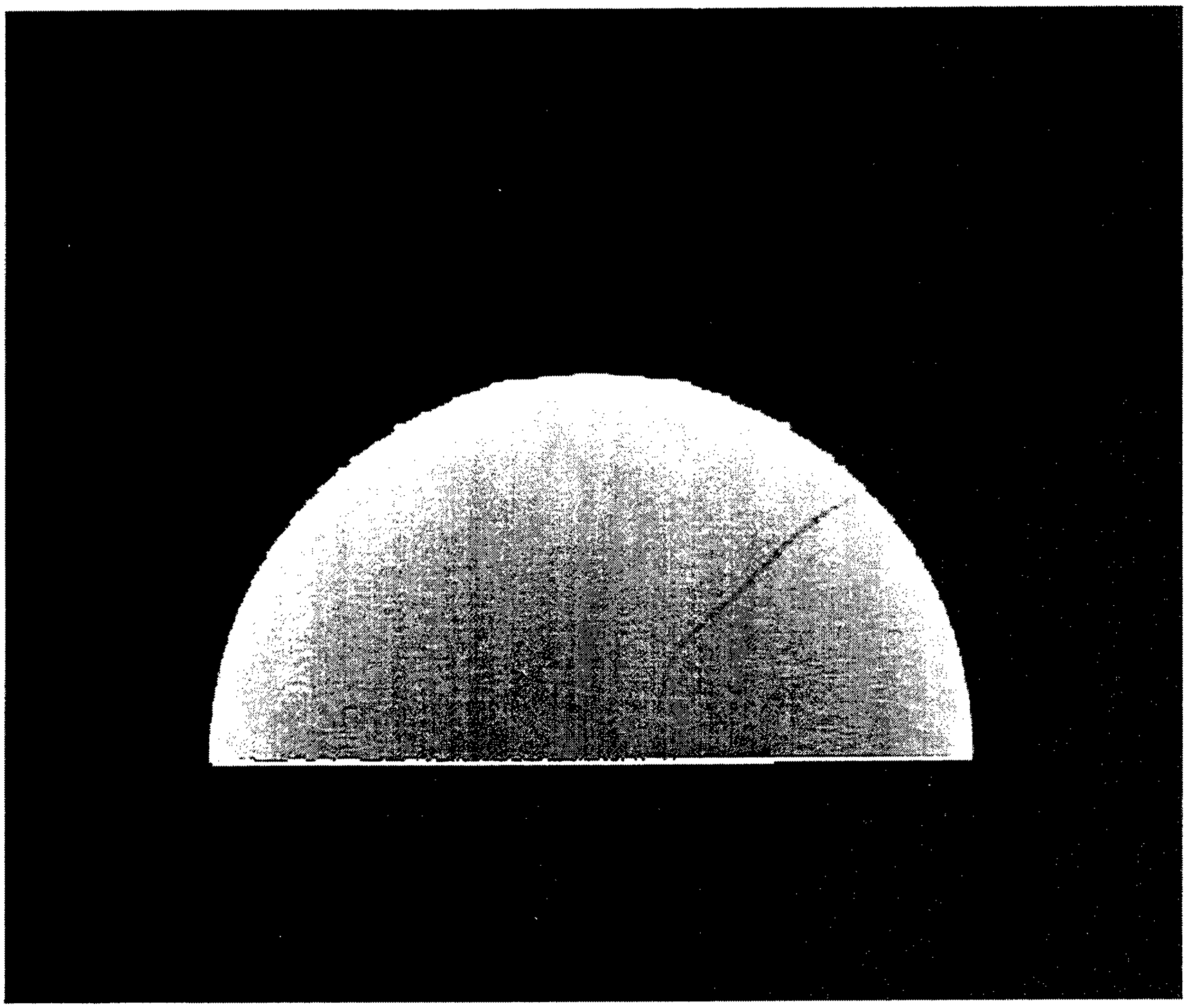

Figure A-3. 1.87 mm from bottom of disk with 65° rotation about X-axis.

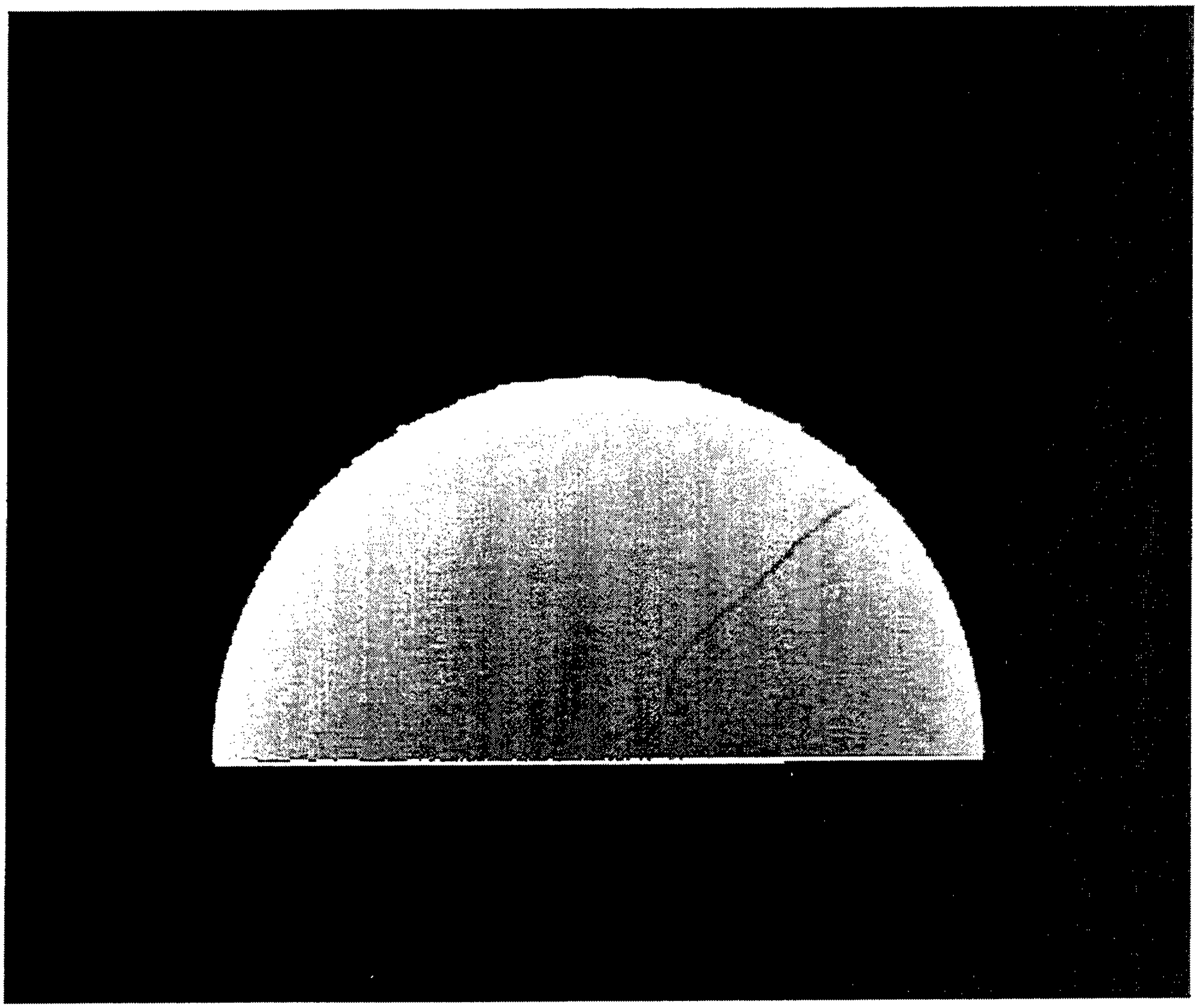

Figure A-4. 2.60 mm from bottom of disk with 65° rotation about X-axis.

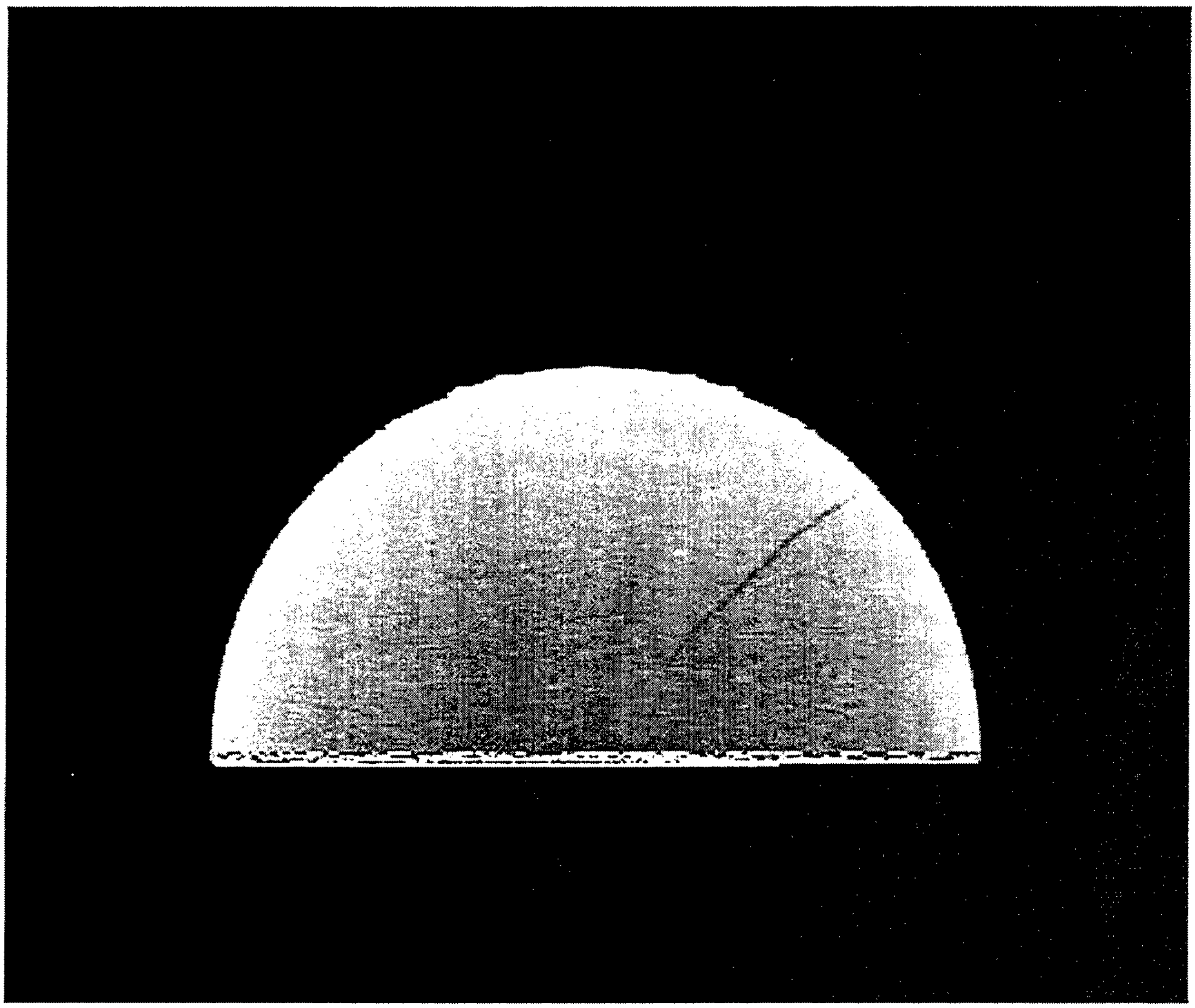

Figure A-5. 3.09 mm from bottom of disk with 65° rotation about X-axis.

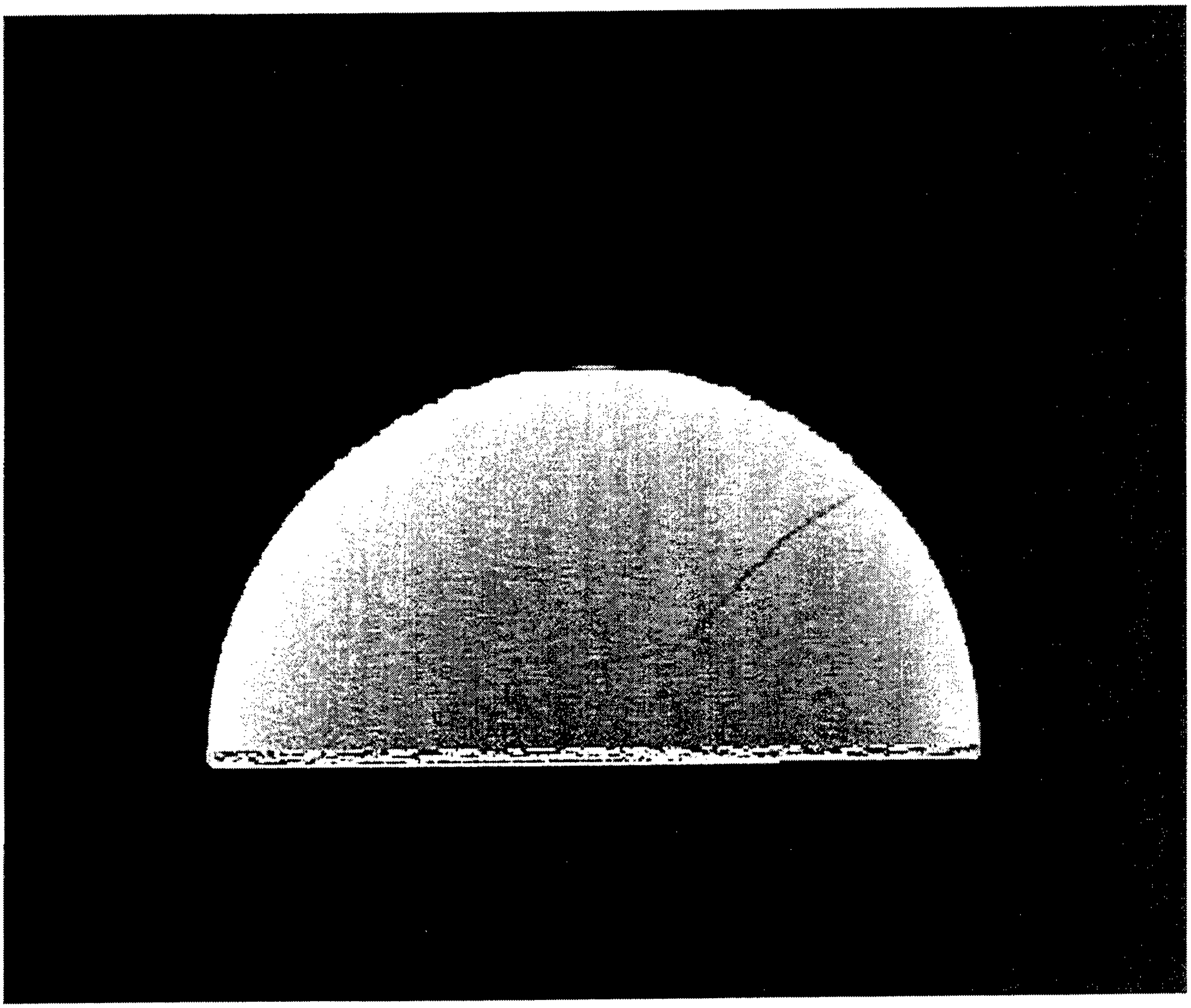

Figure A-6. 3.82 mm from bottom of disk with 65° rotation about X-axis.

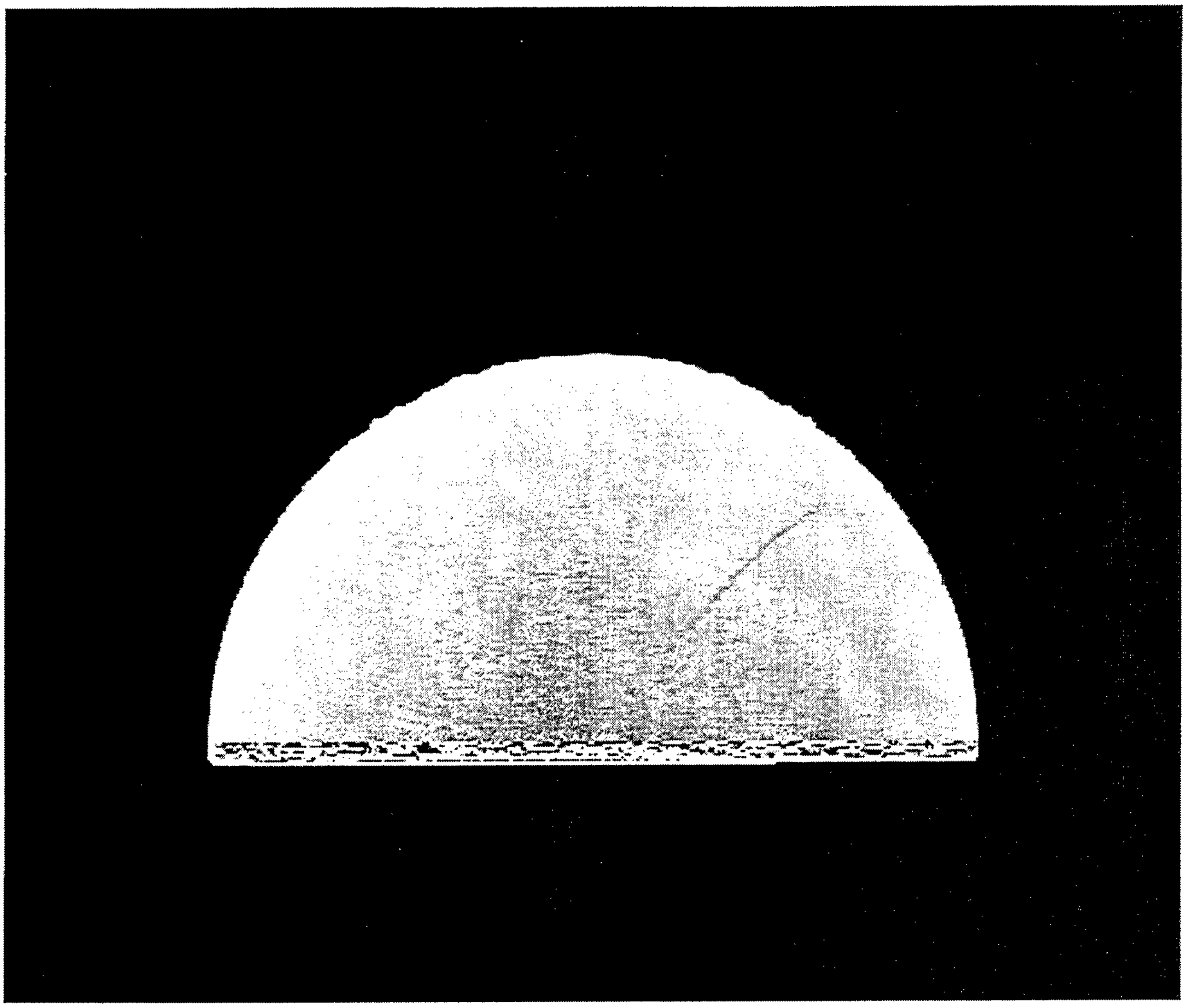

Figure A-7. 4.51 mm from bottom of disk with 65° rotation about X-axis.

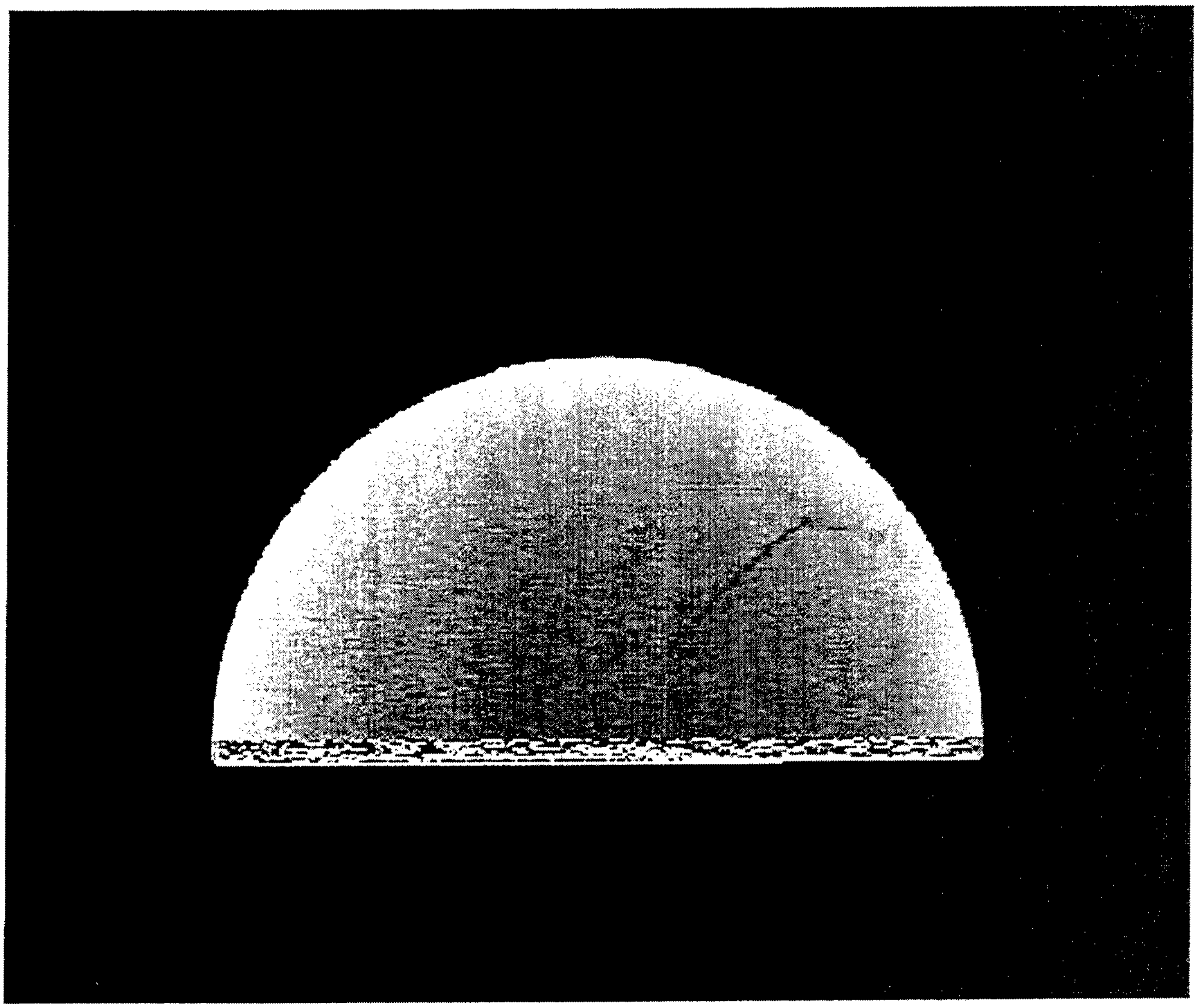

Figure A-8. 5.04 mm from bottom of disk with 65° rotation about X-axis.

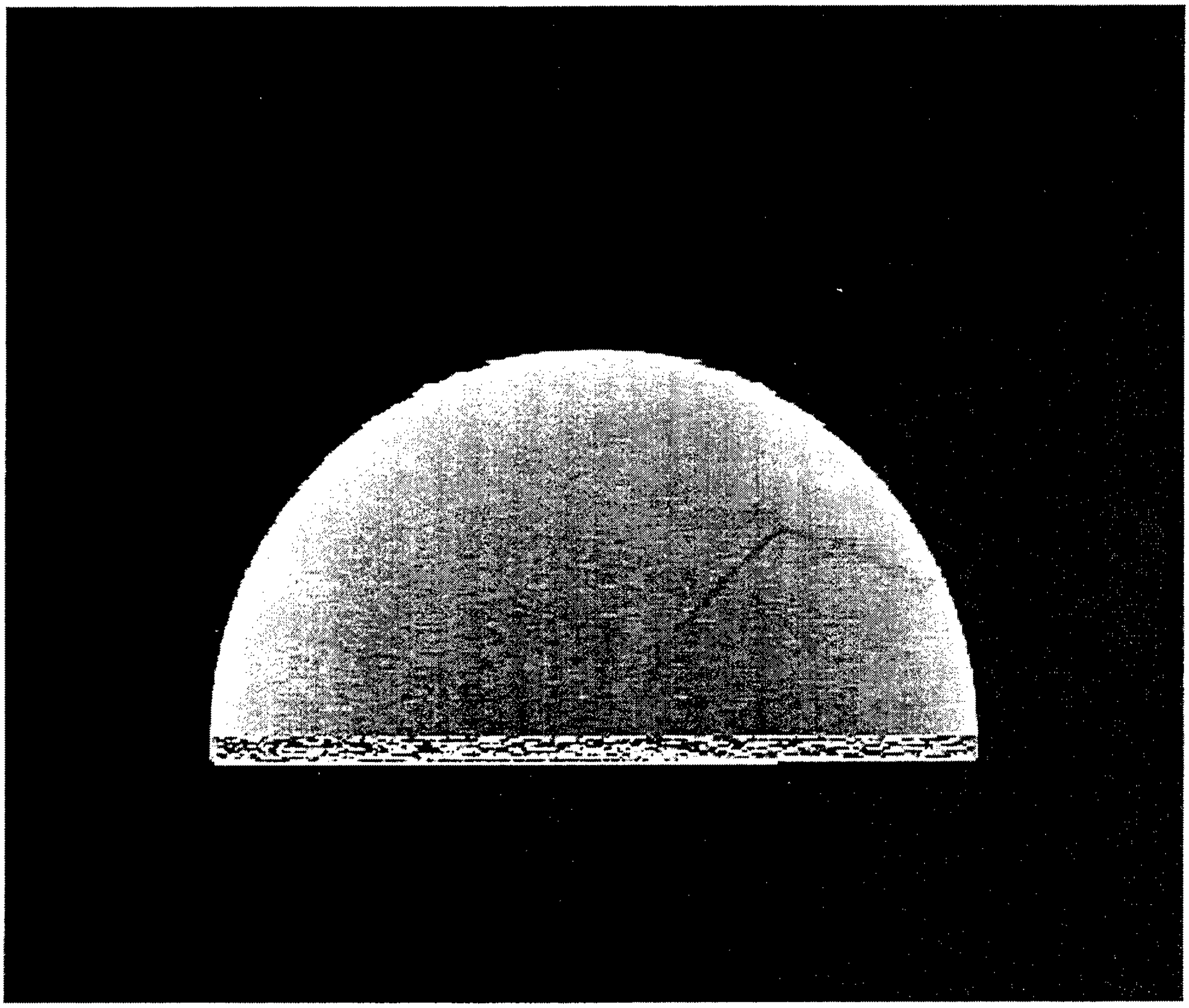

Figure A-9. 5.53 mm from bottom of disk with 65° rotation about X-axis.

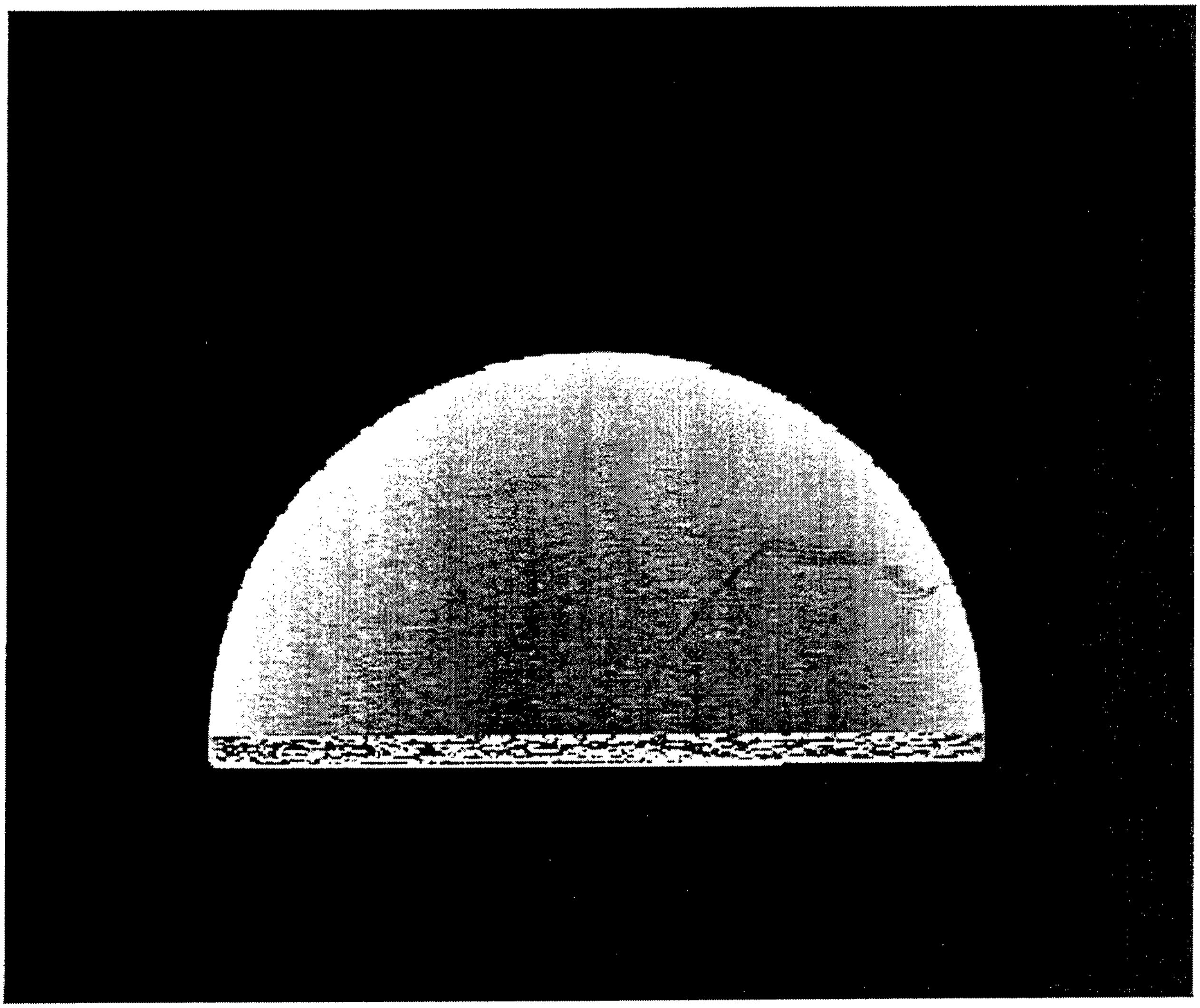

Figure A-10. 6.26 mm from bottom of disk with 65° rotation about X-axis.

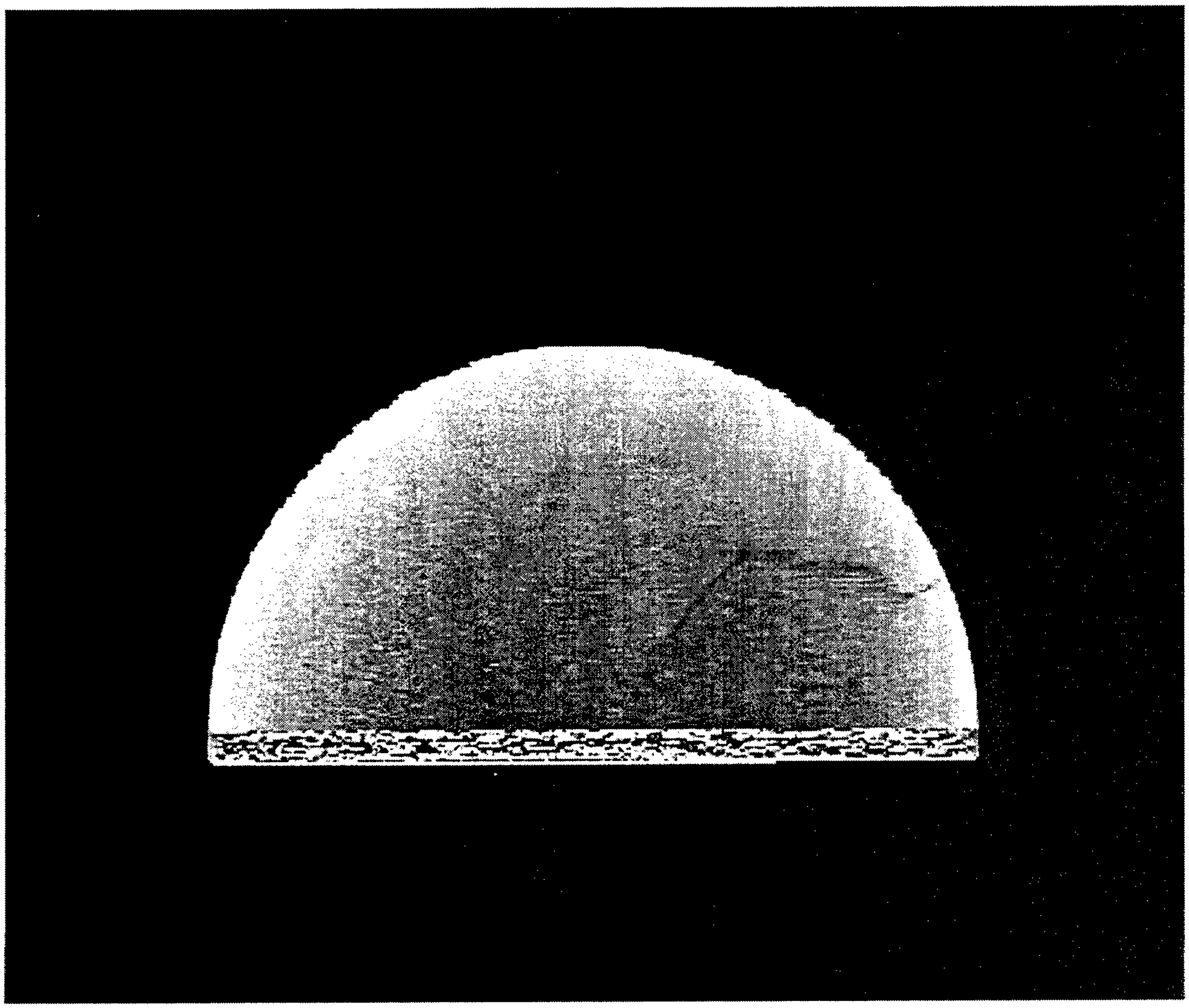

Figure A-11. 6.75 mm from bottom of disk with 65° rotation about X-axis.

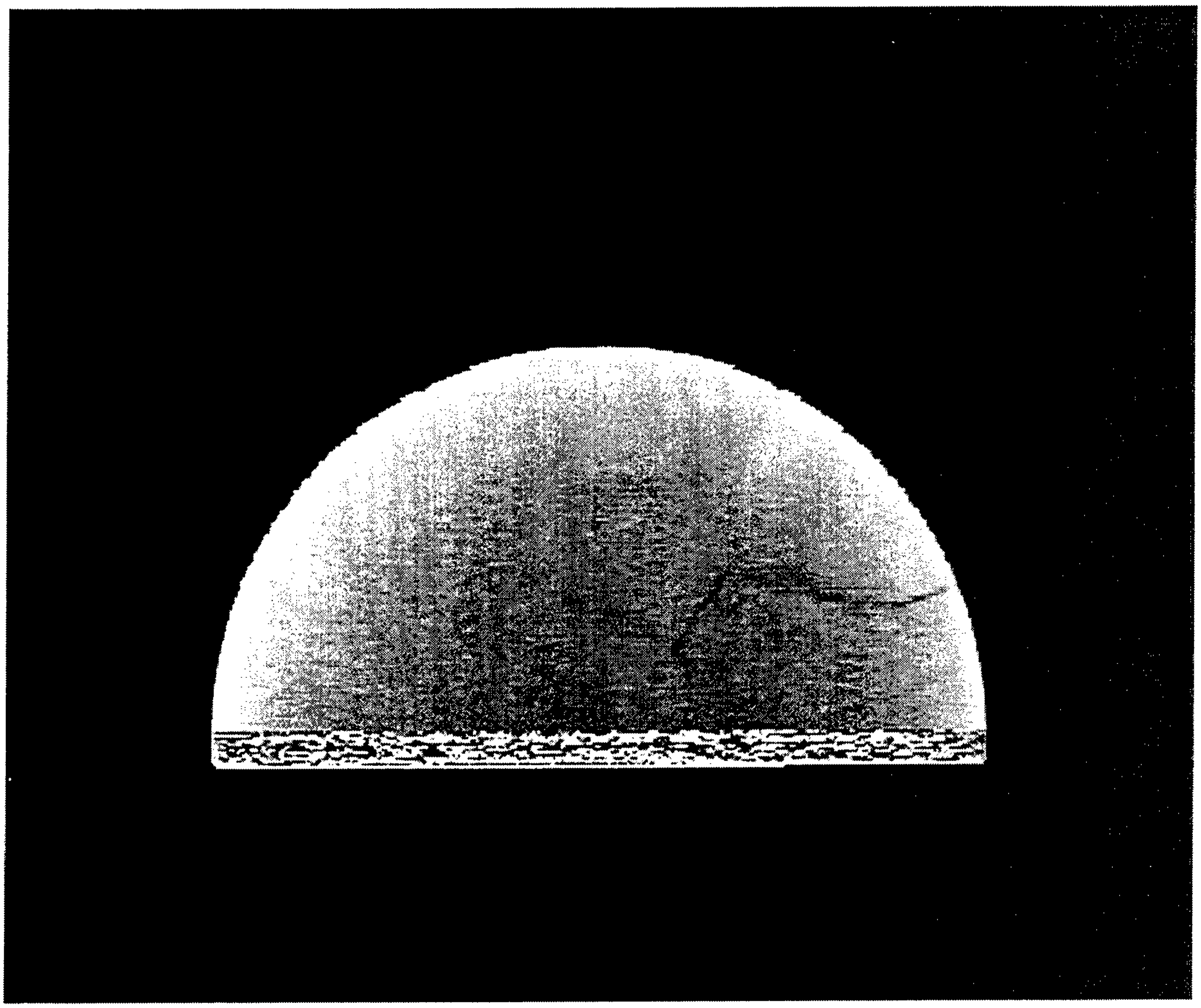

Figure A-12. 7.24 mm from bottom of disk with 65° rotation about X-axis.

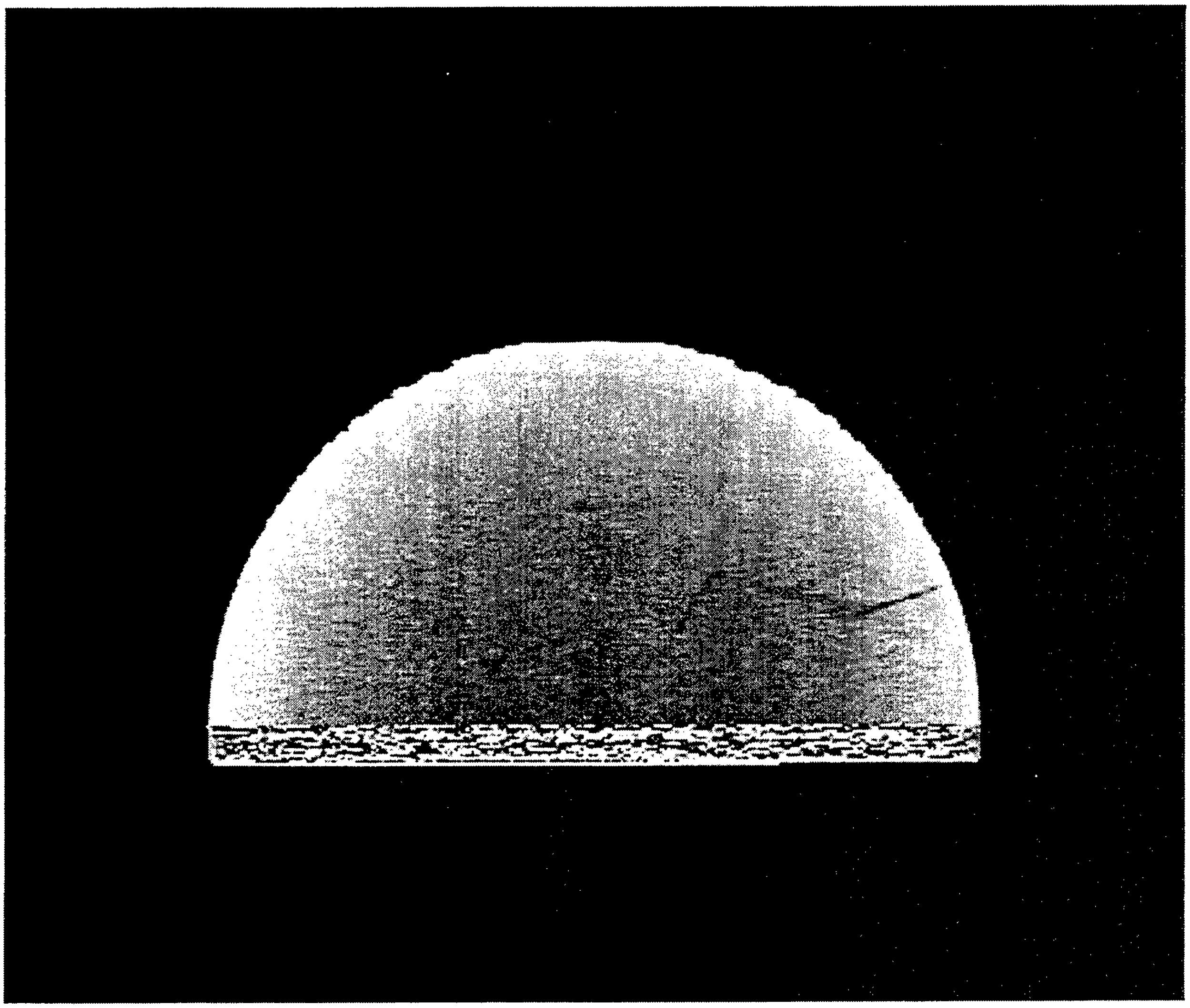

Figure A-13. 7.97 mm from bottom of disk with 65° rotation about X-axis.

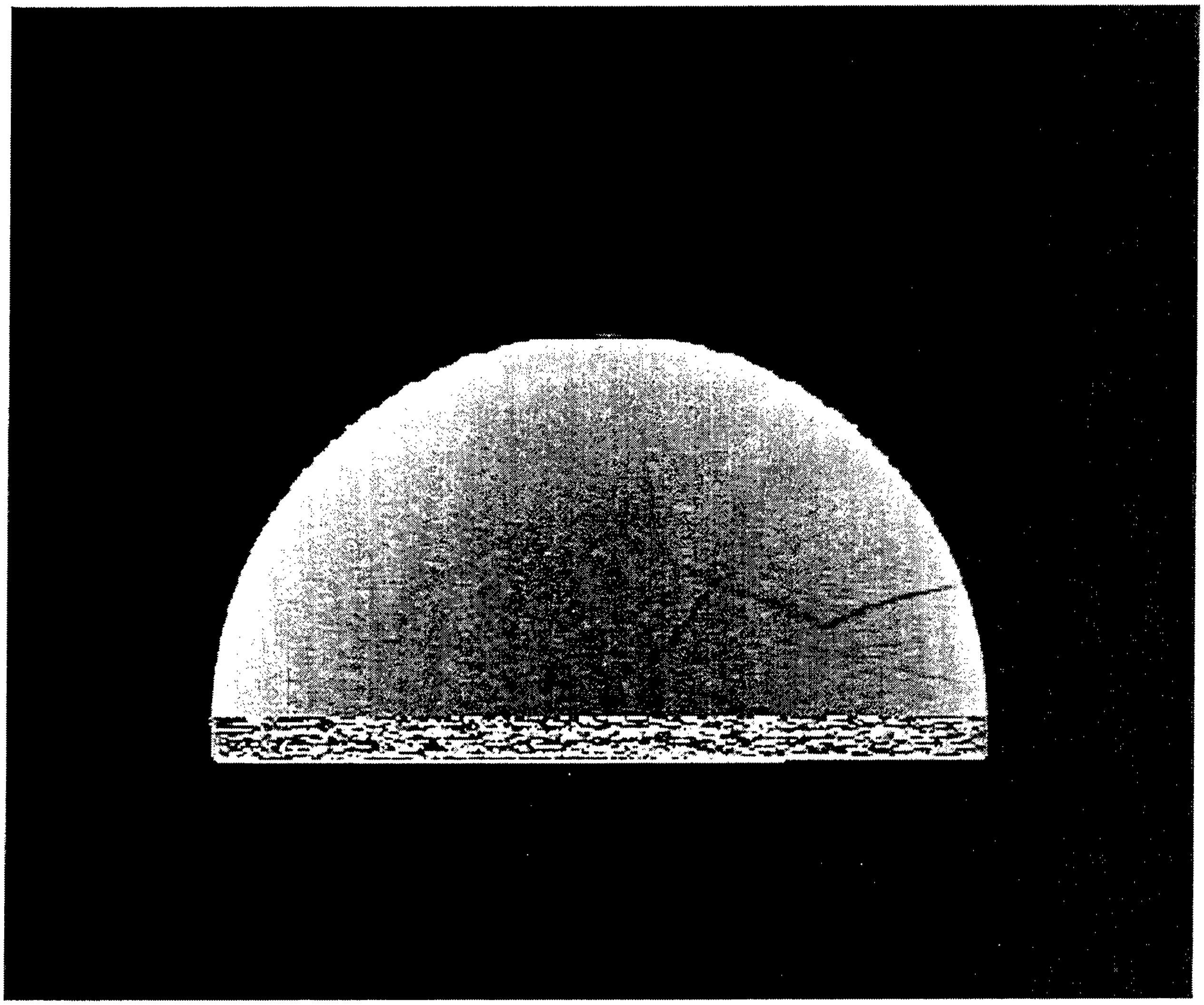

Figure A-14. 8.46 mm from bottom of disk with 65° rotation about X-axis.

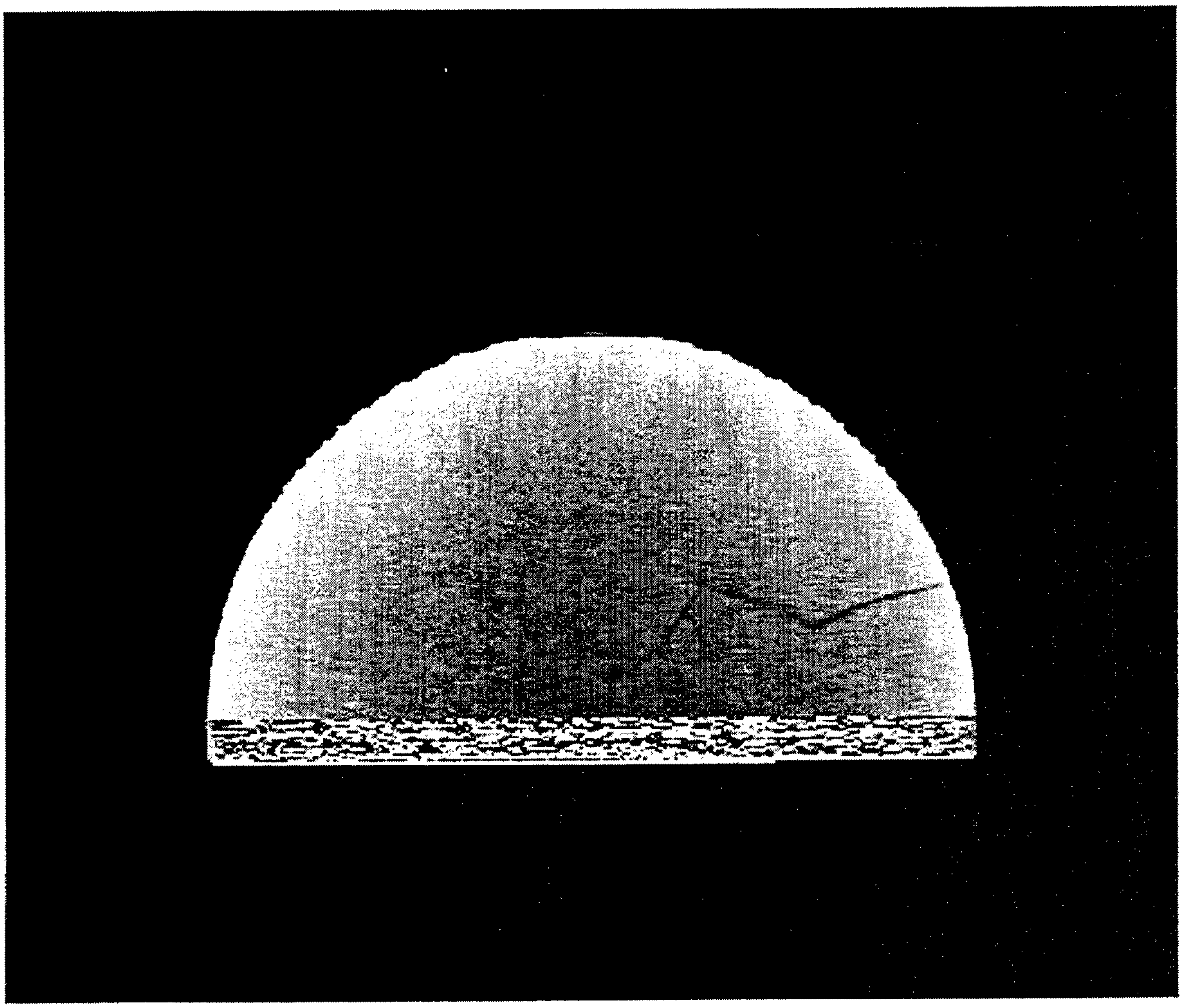

Figure A-15. 9.19 mm from bottom of disk with 65° rotation about X-axis.

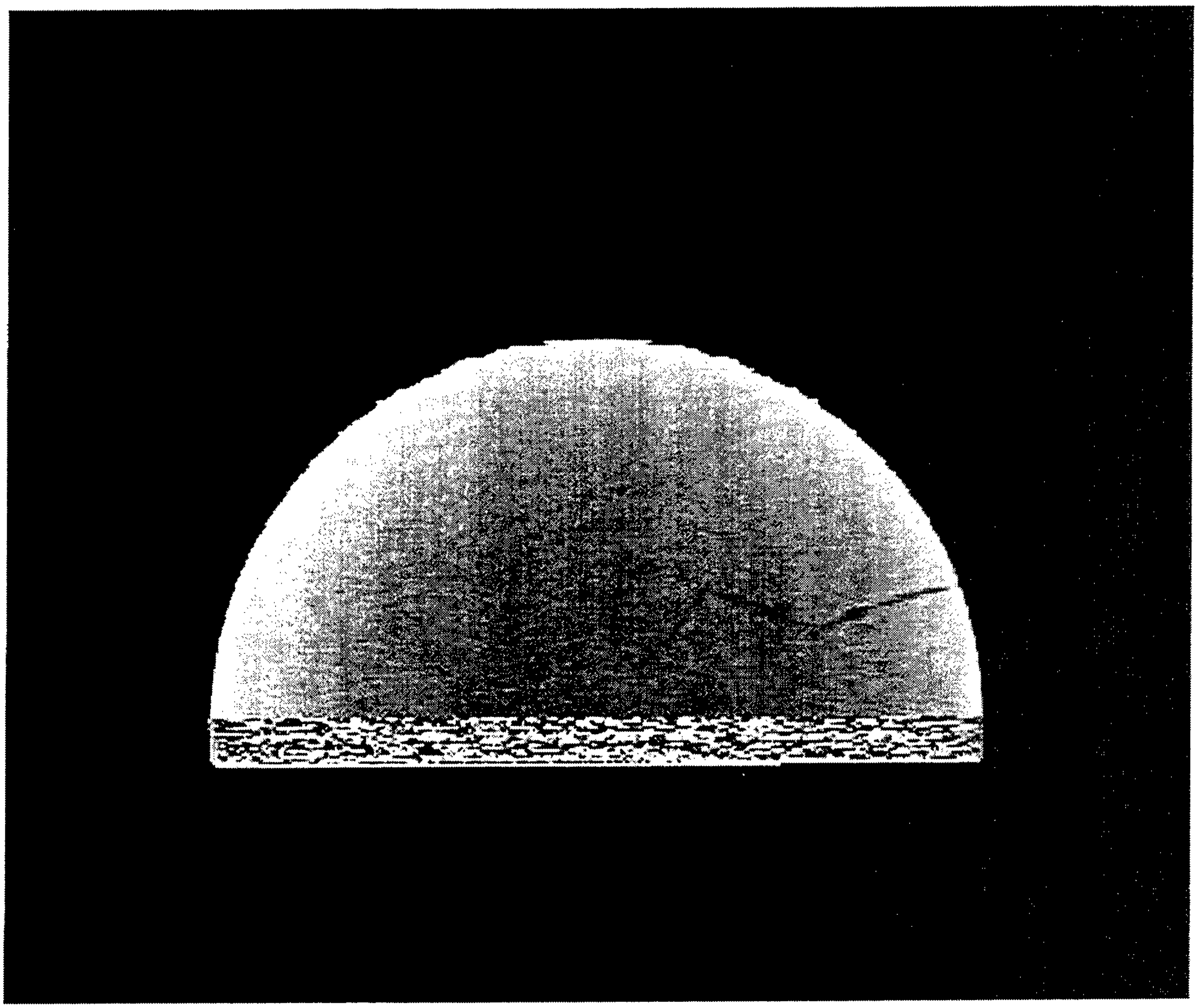

Figure A-16. 9.68 mm from bottom of disk with 65° rotation about X-axis.

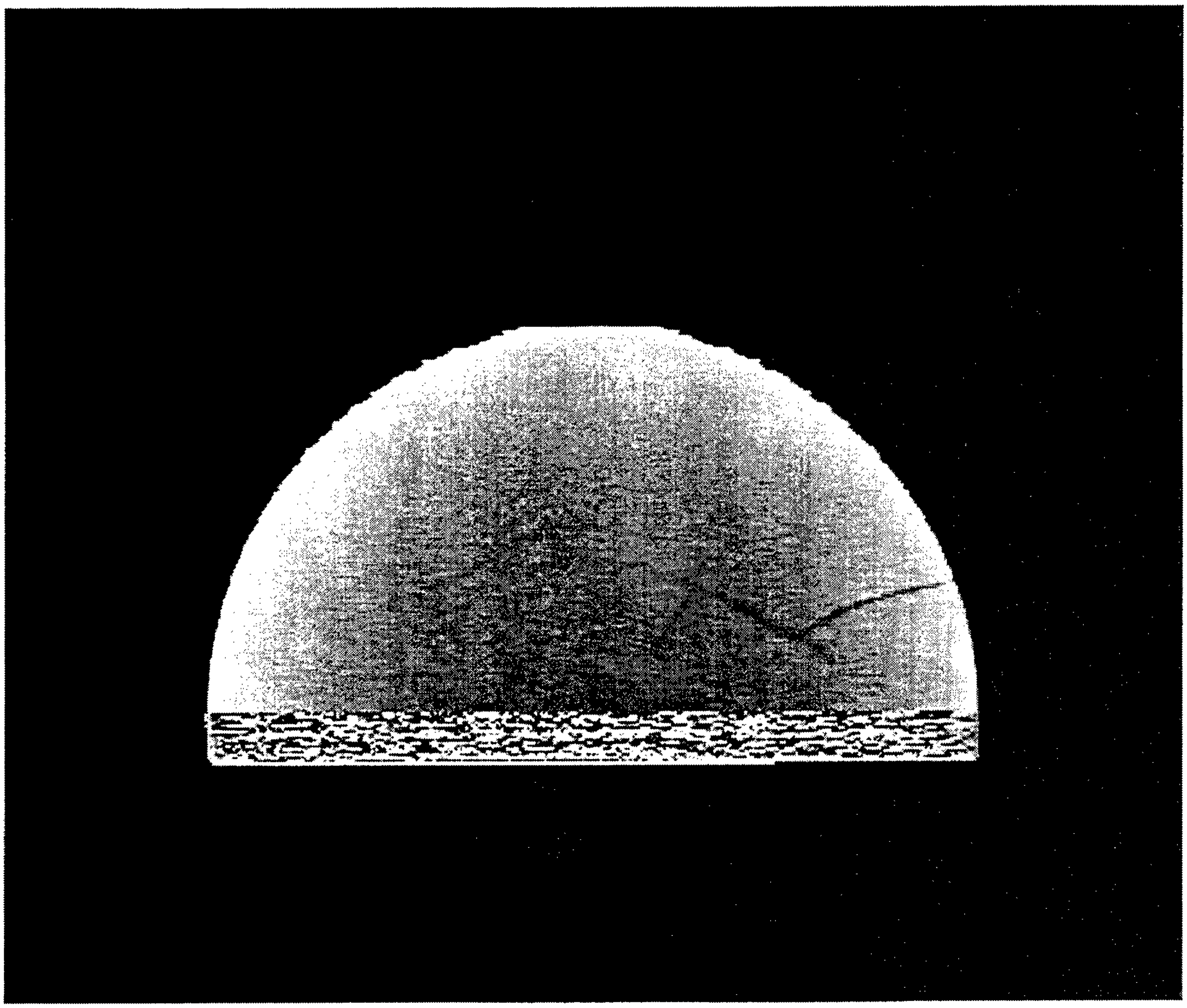

Figure A-17. 10.17 mm from bottom of disk with 65° rotation about X-axis.

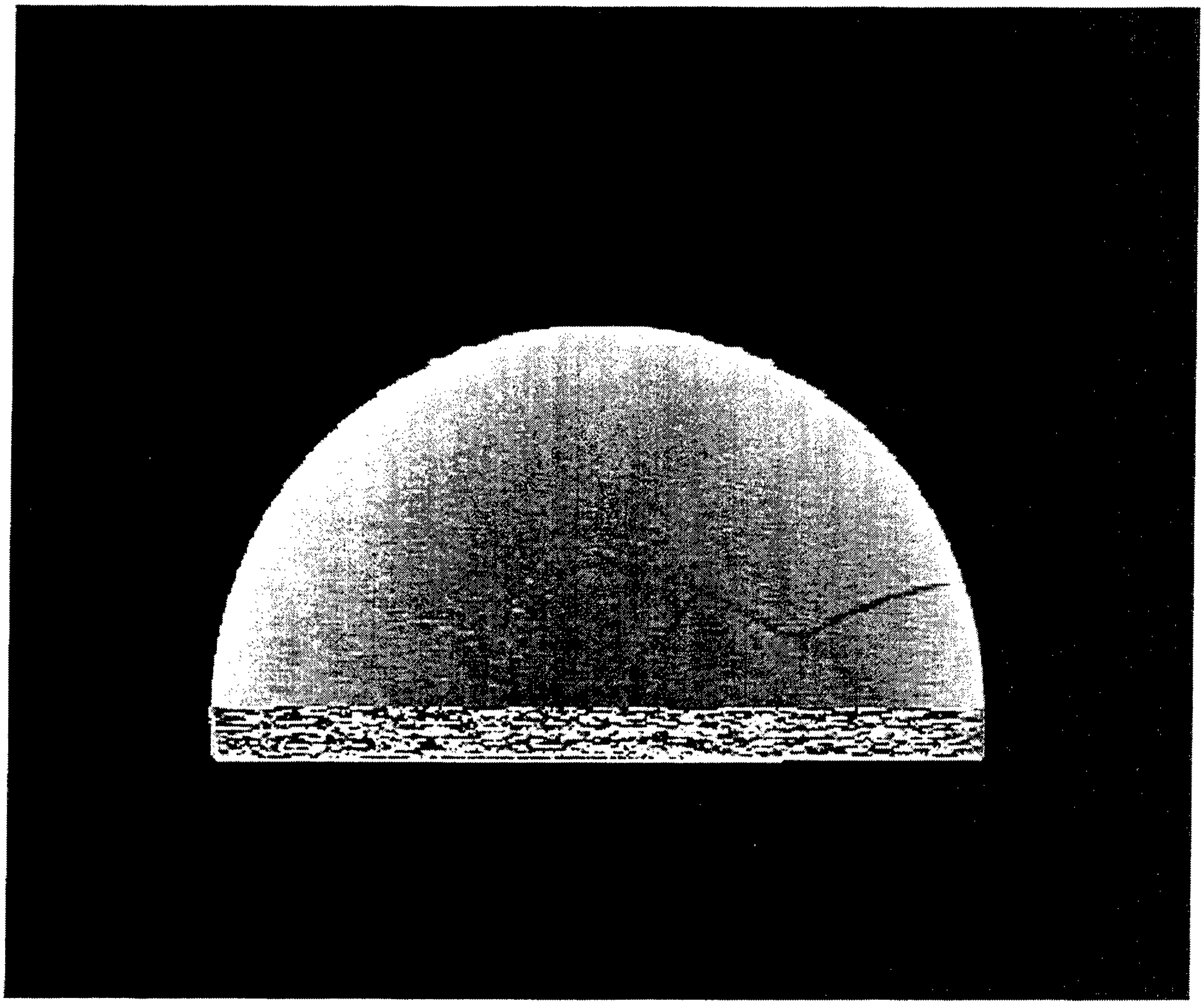

Figure A-18. 10.90 mm from bottom of disk with 65° rotation about X-axis.

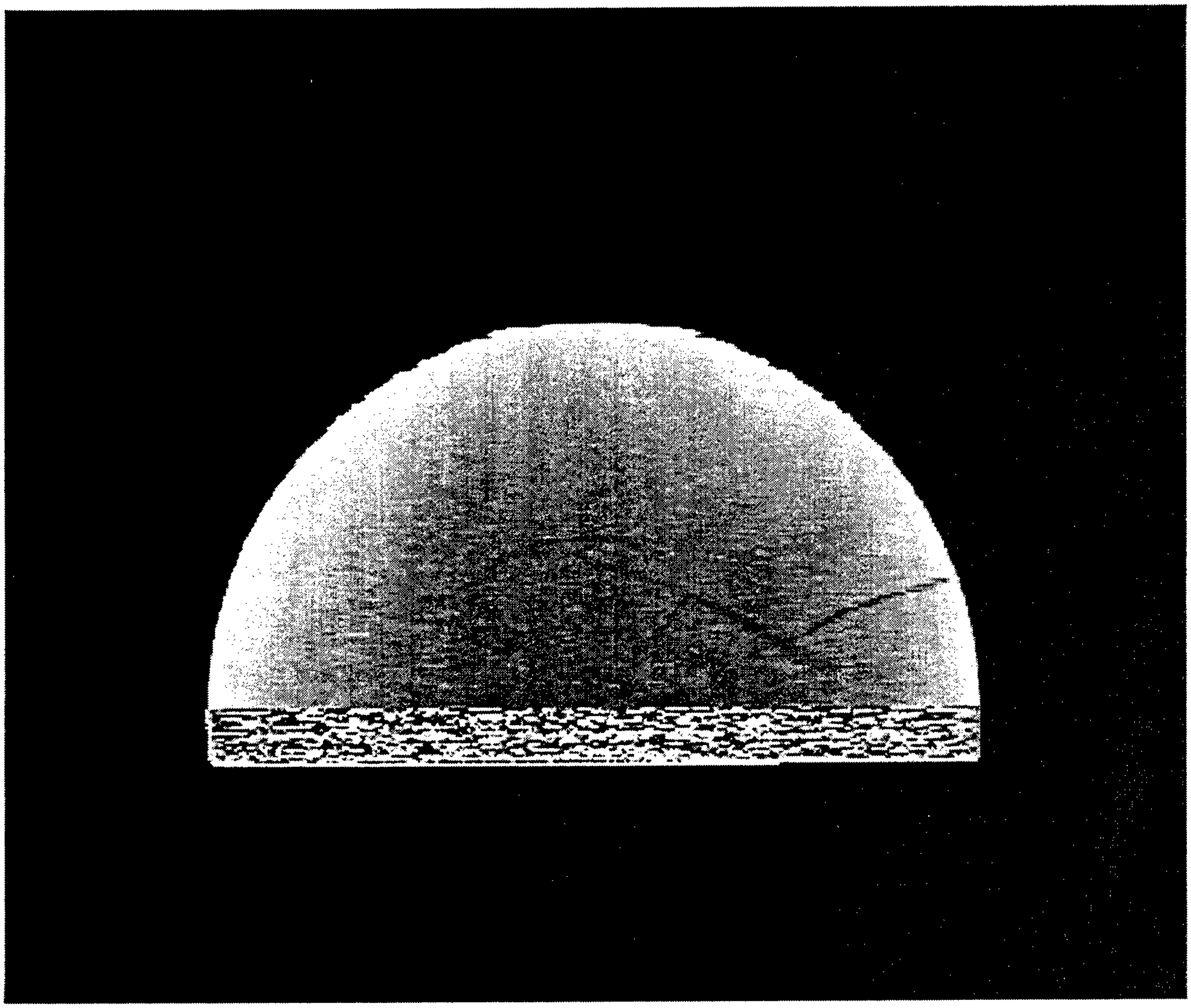

Figure A-19. 11.39 mm from bottom of disk with 65° rotation about X-axis.

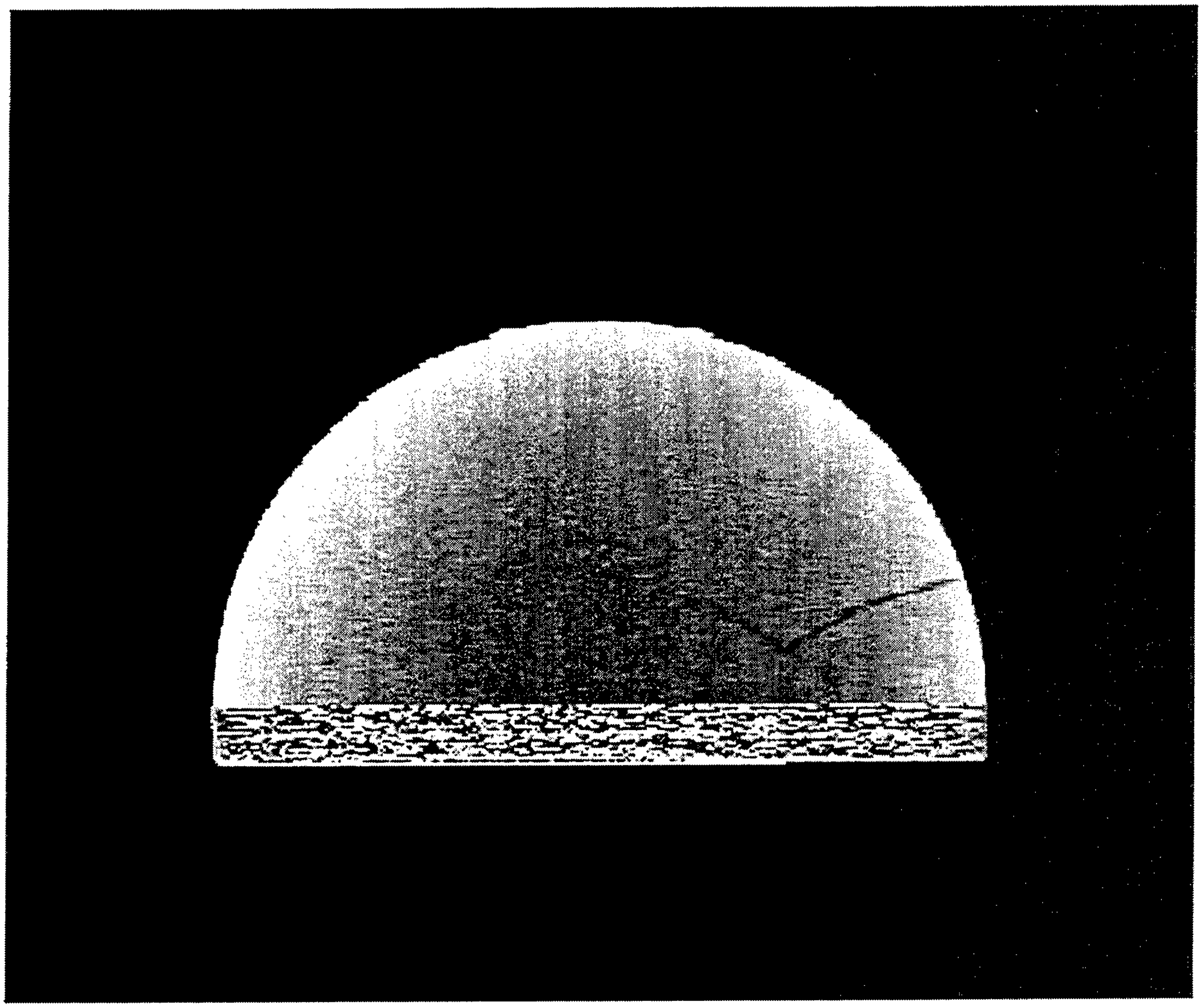

Figure A-20. 12.12 mm from bottom of disk with 65° rotation about X-axis.

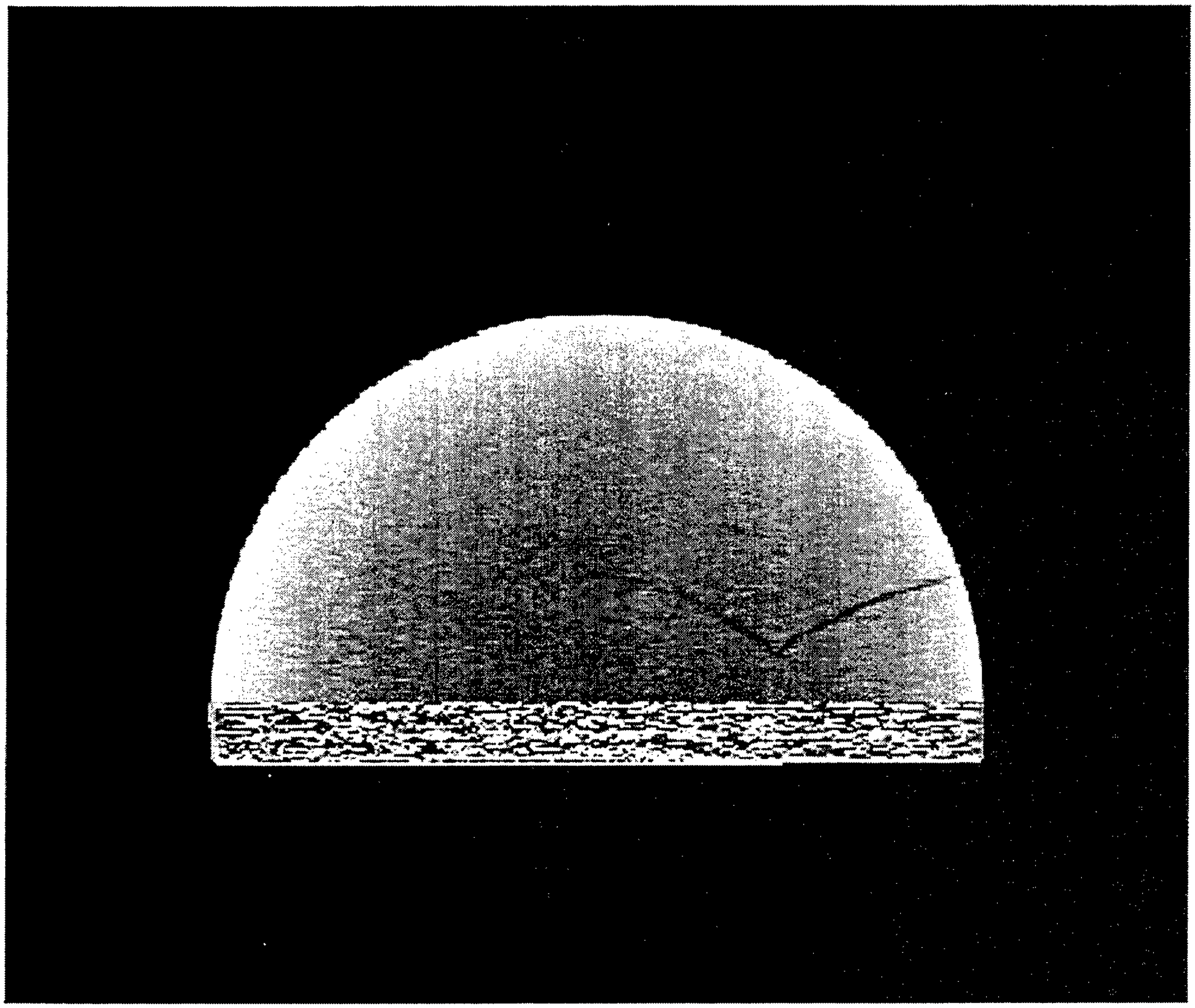

Figure A-21. 12.61 mm from bottom of disk with 65° rotation about X-axis.

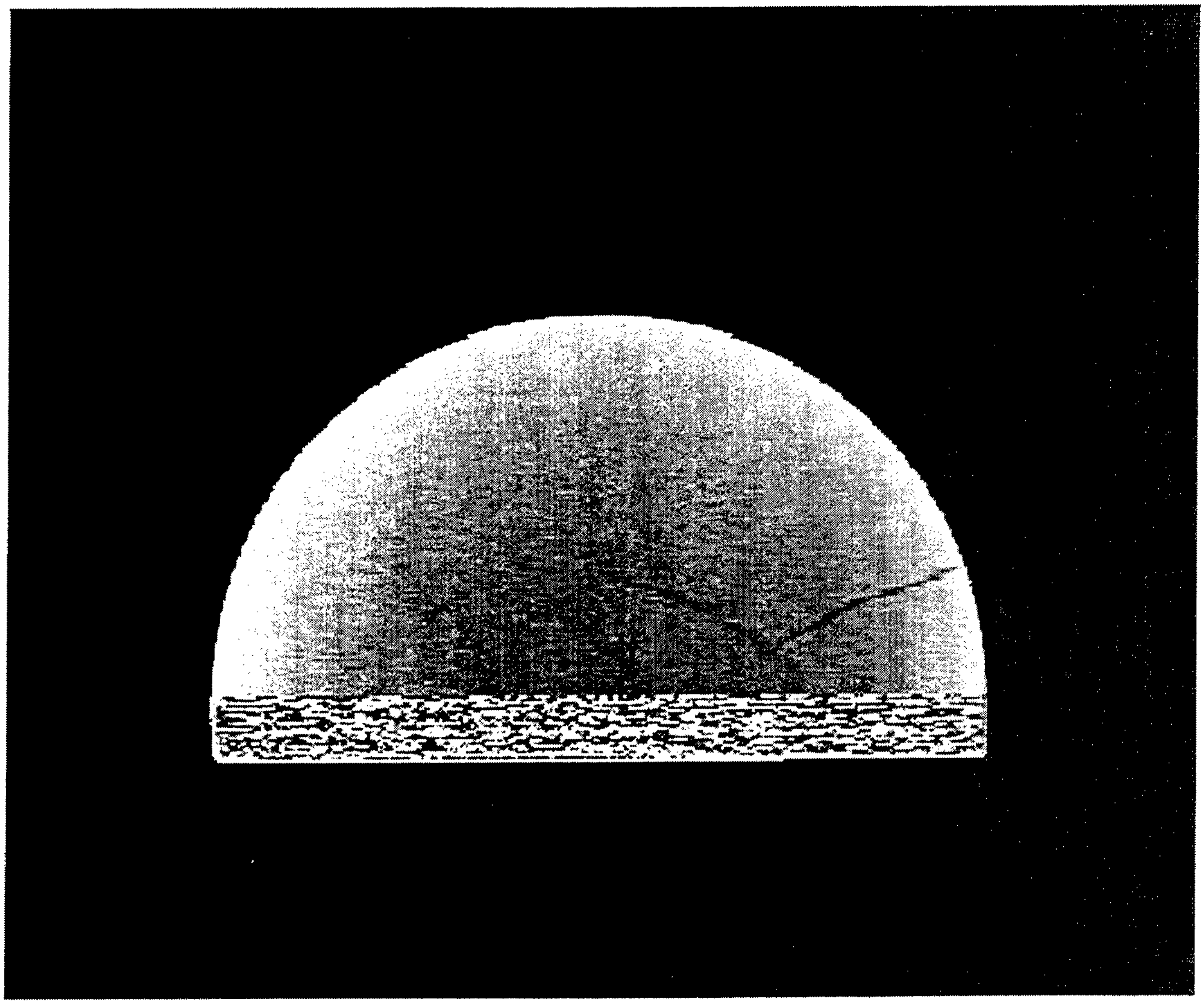

Figure A-22. 13.10 mm from bottom of disk with 65° rotation about X-axis.

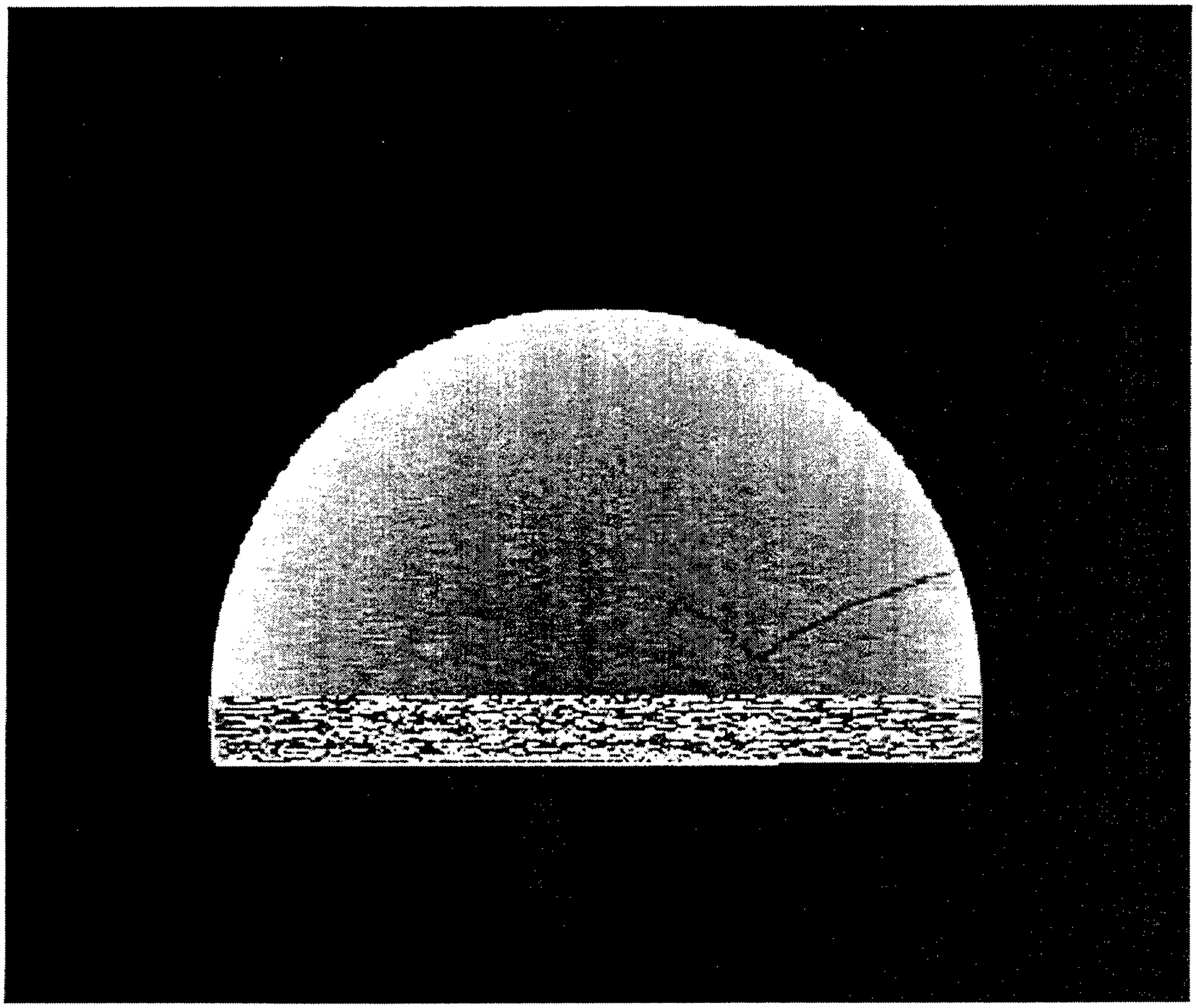

Figure A-23. 13.83 mm from bottom of disk with 65° rotation about X-axis.

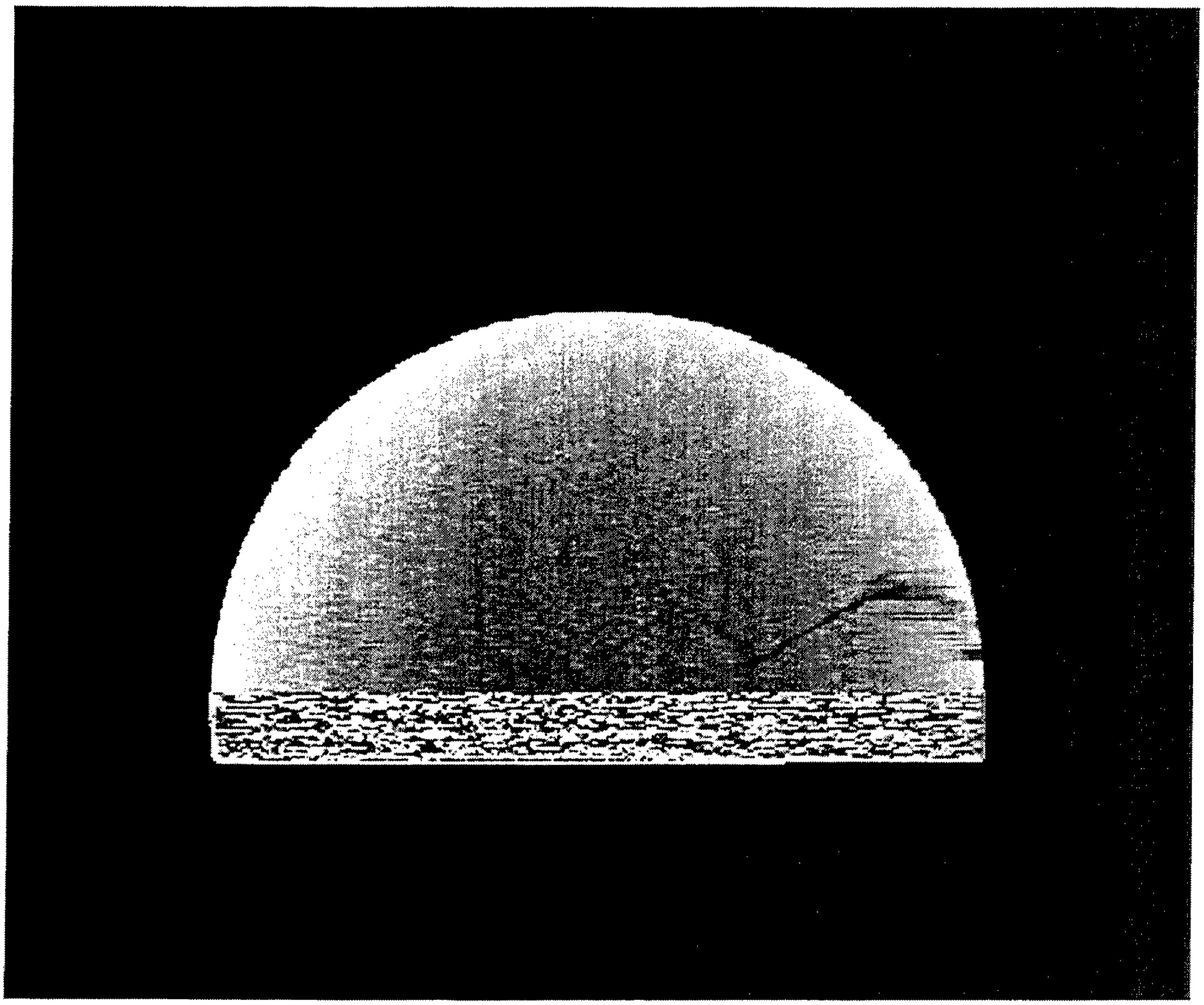

Figure A-24. 14.32 mm from bottom of disk with 65° rotation about X-axis.

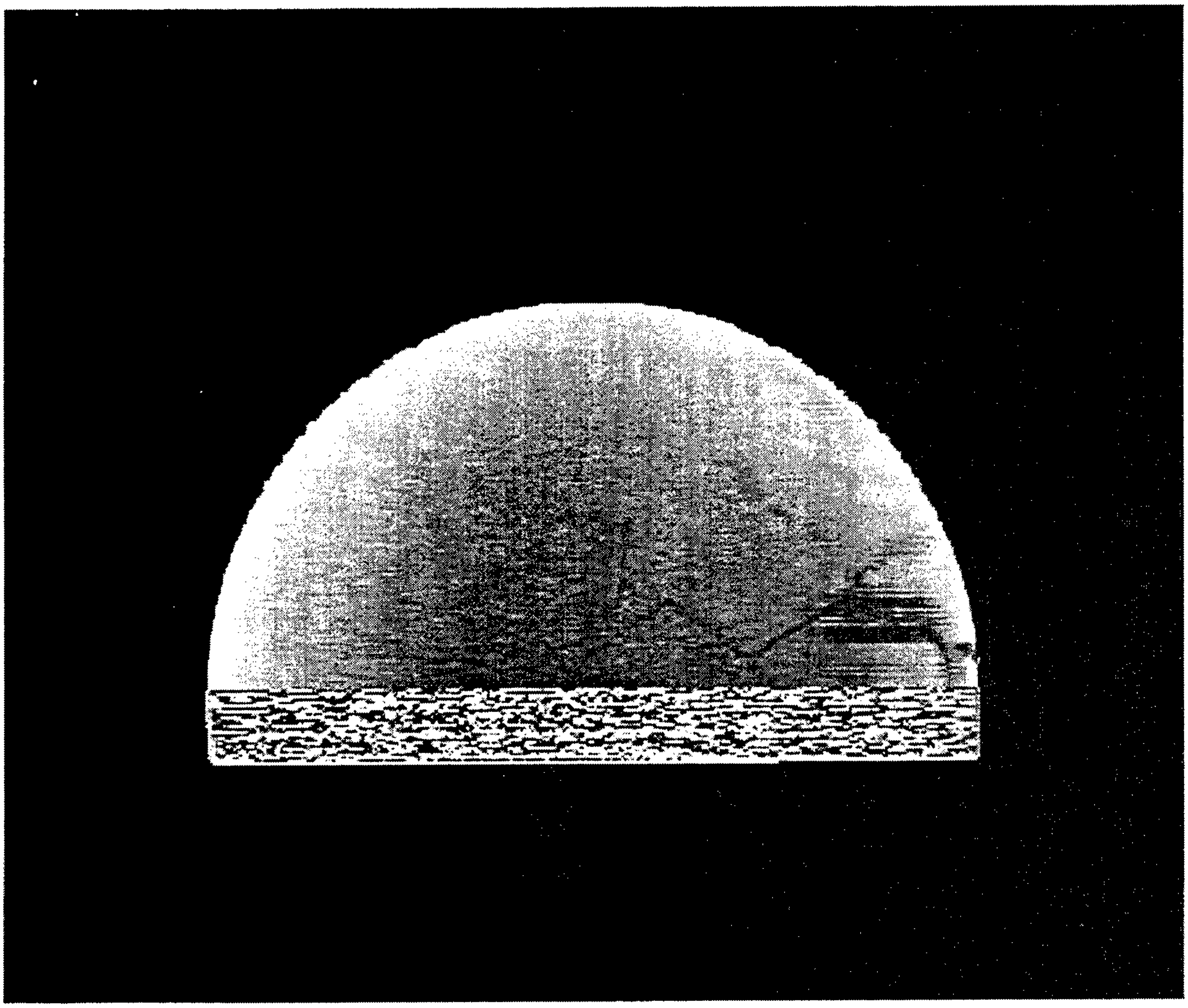

Figure A-25. 15.05 mm from bottom of disk with 65° rotation about X-axis.

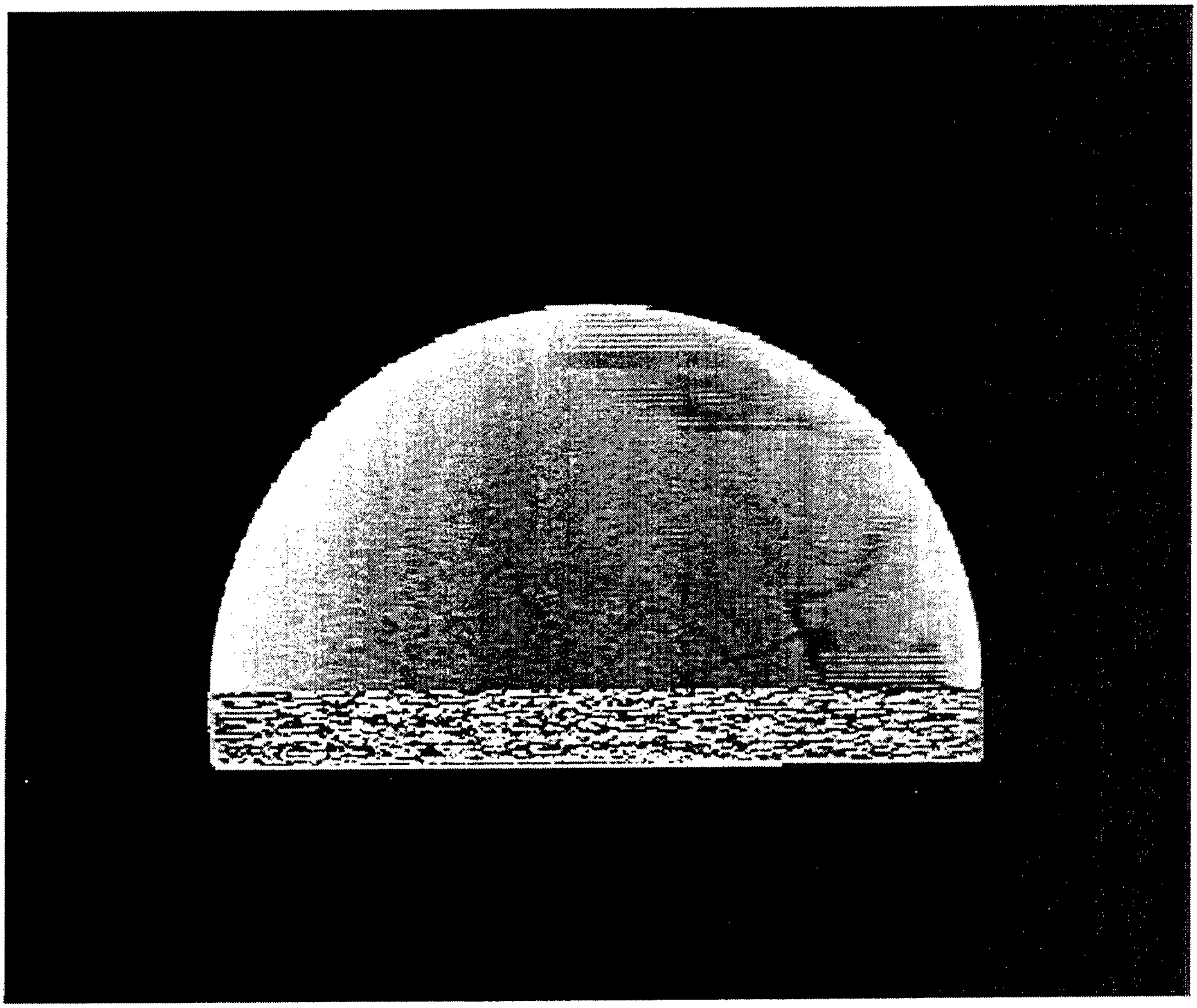

Figure A-26. 15.54 mm from bottom of disk with 65° rotation about X-axis.

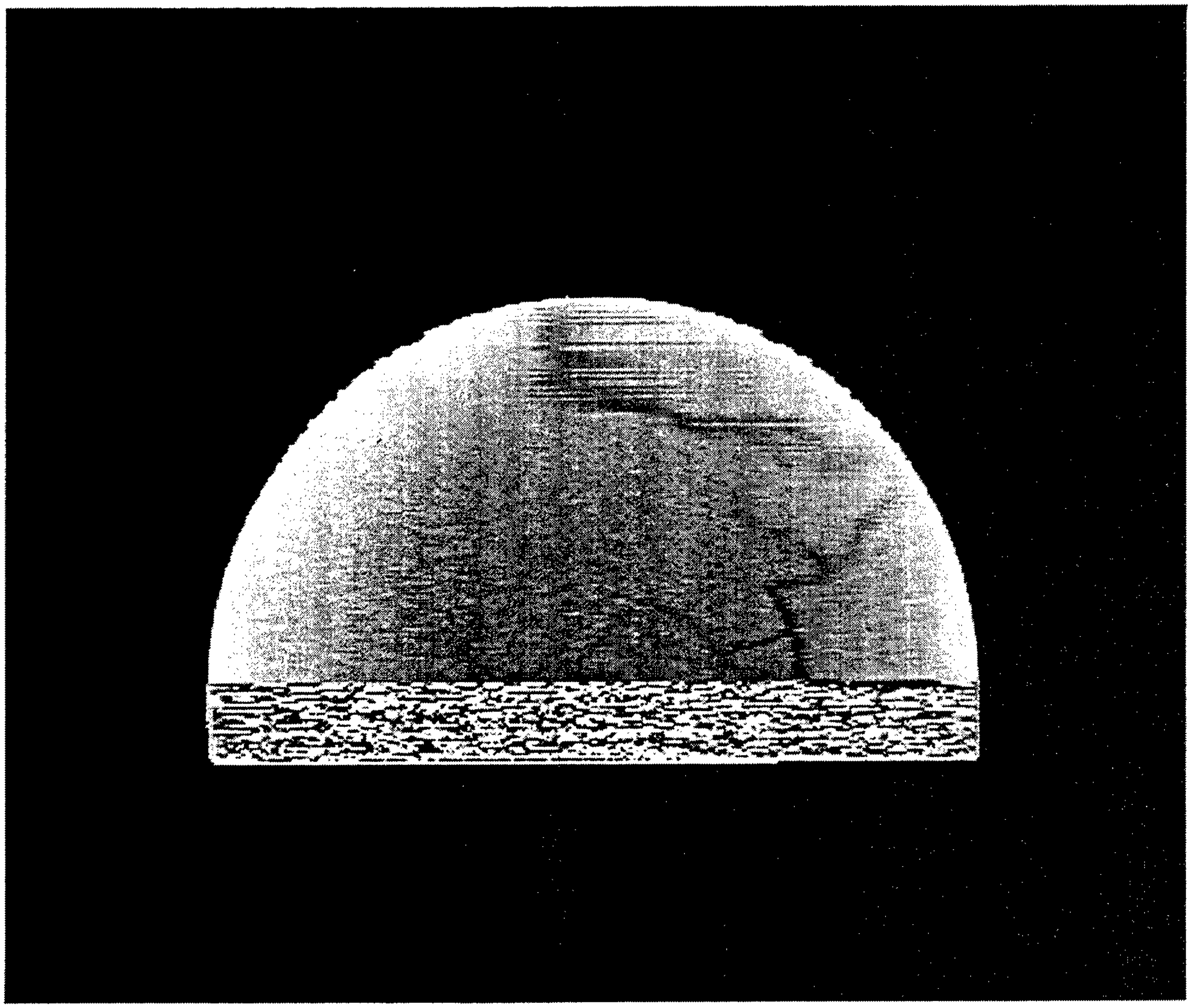

Figure A-27. 16.27 mm from bottom of disk with 65° rotation about X-axis.

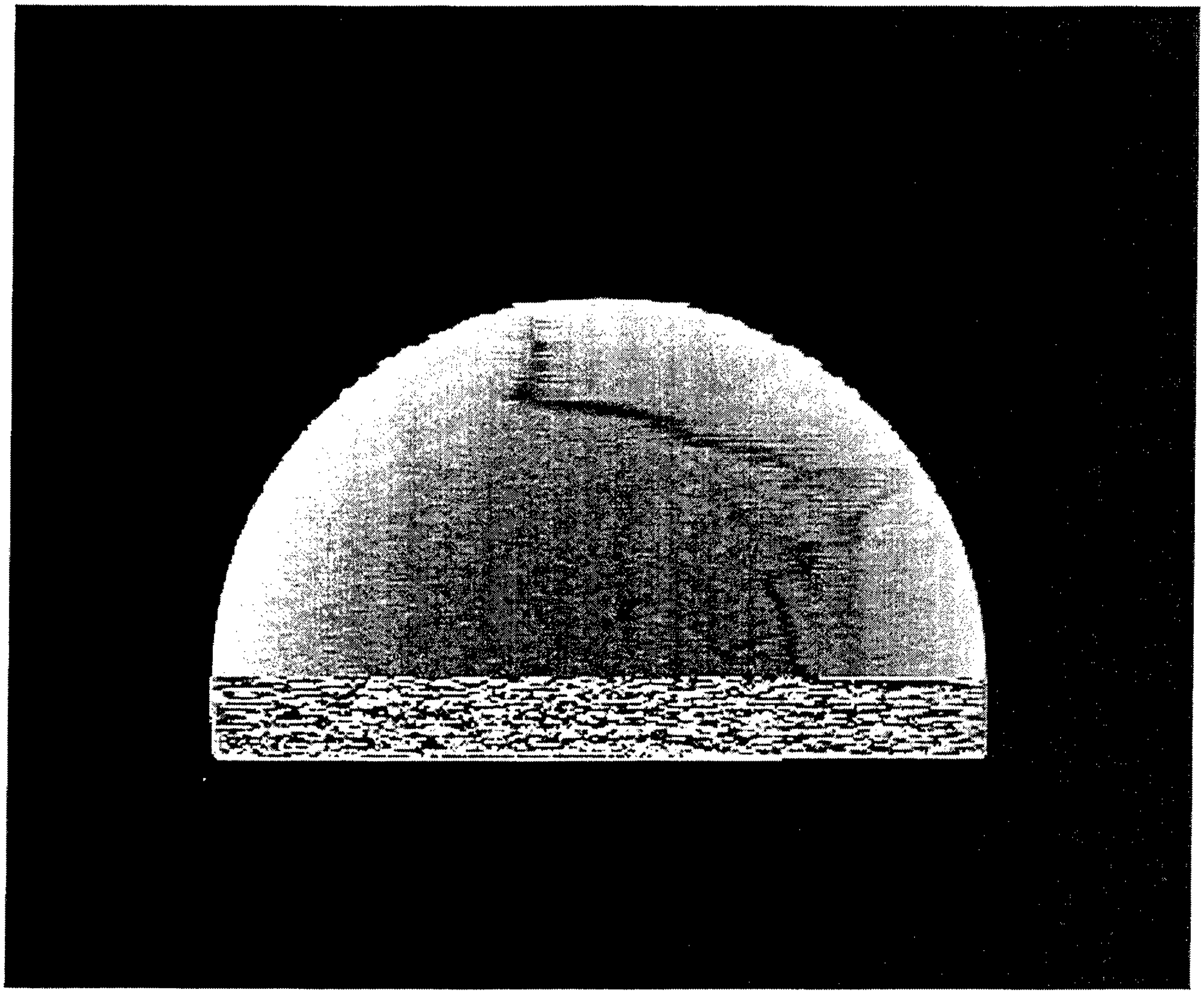

Figure A-28. 16.76 mm from bottom of disk with 65° rotation about X-axis.

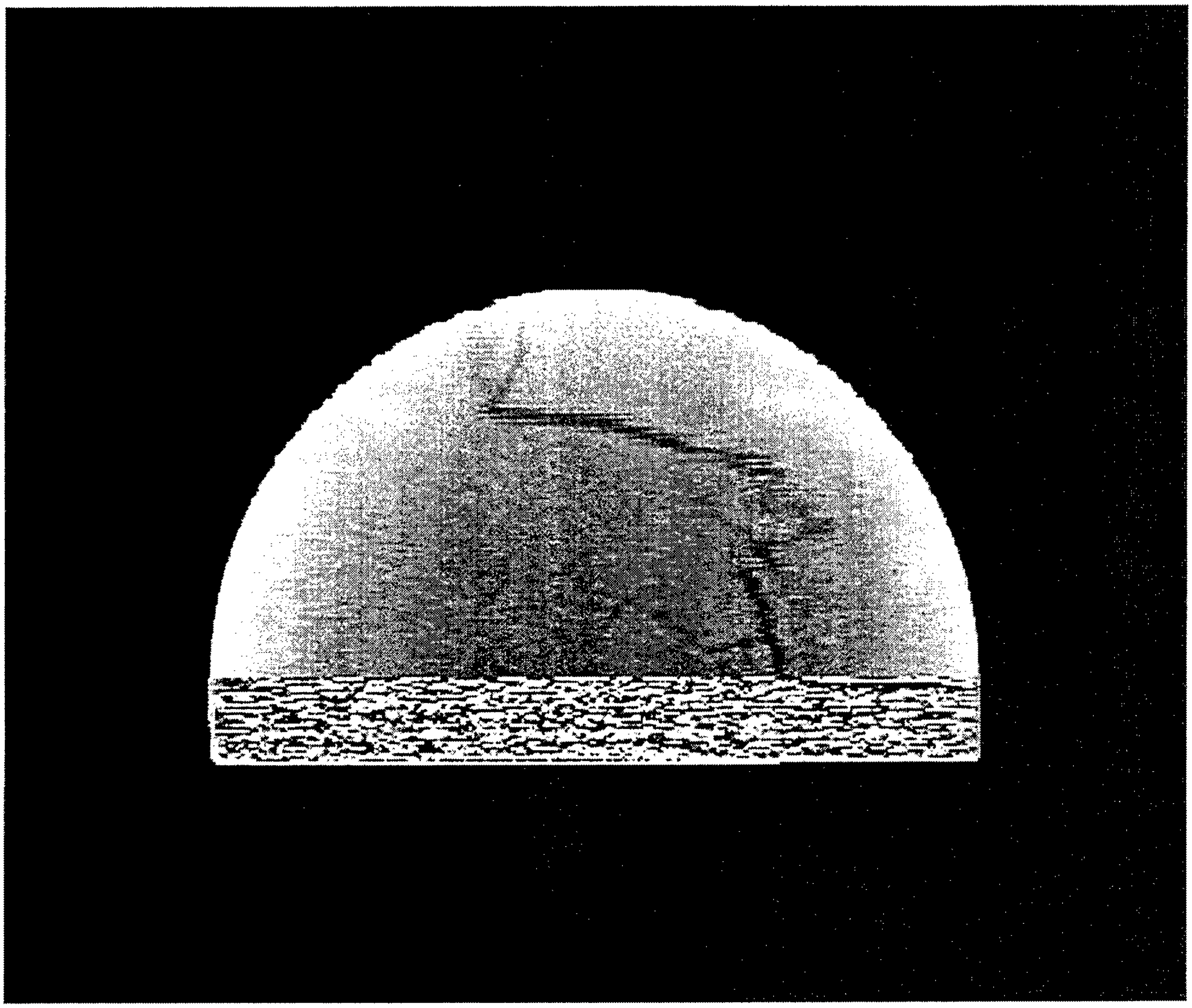

Figure A-29. 17.25 mm from bottom of disk with 65° rotation about X-axis.

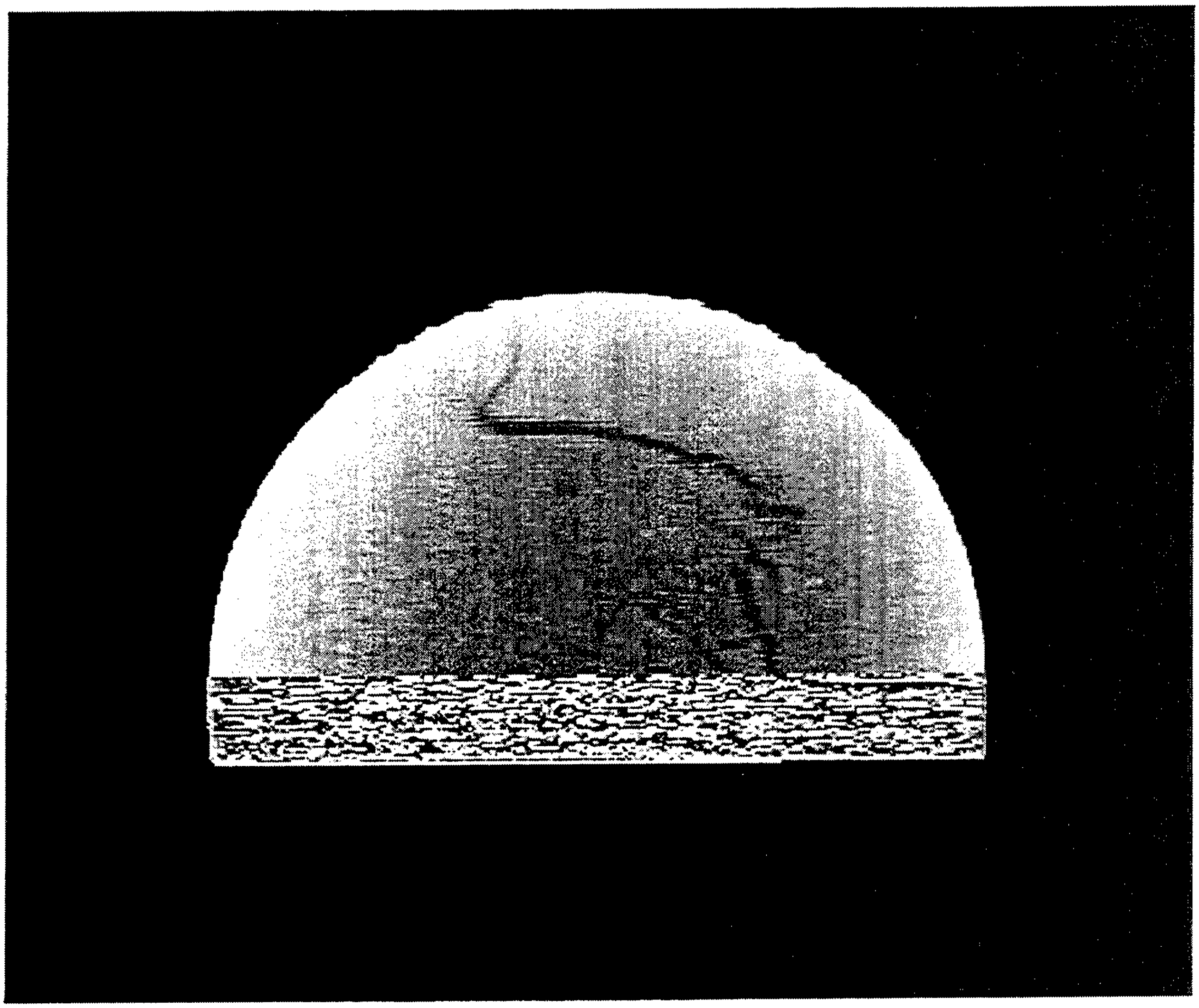

Figure A-30. 17.98 mm from bottom of disk with 65° rotation about X-axis.

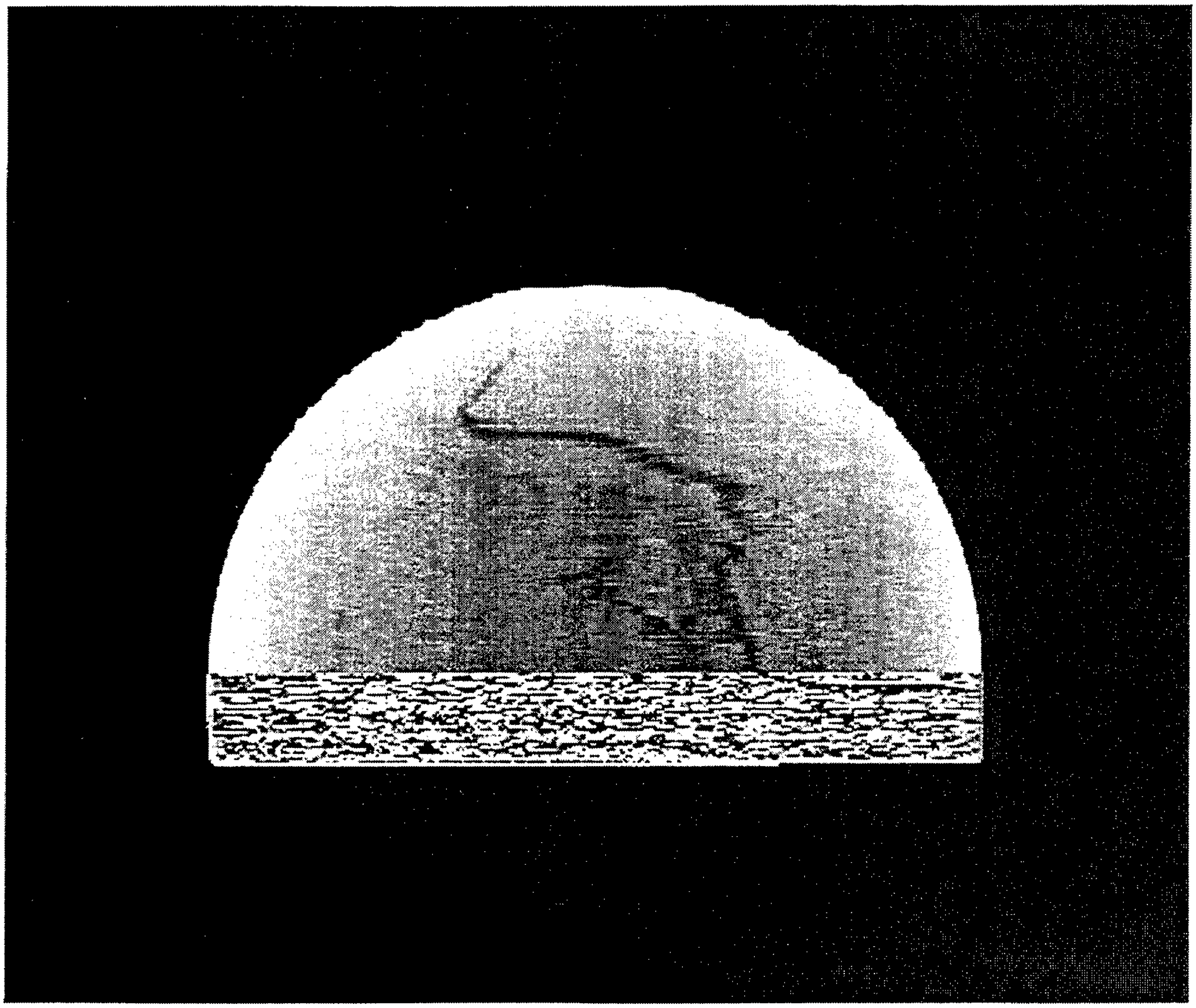

Figure A-31. 18.47 mm from bottom of disk with 65° rotation about X-axis.

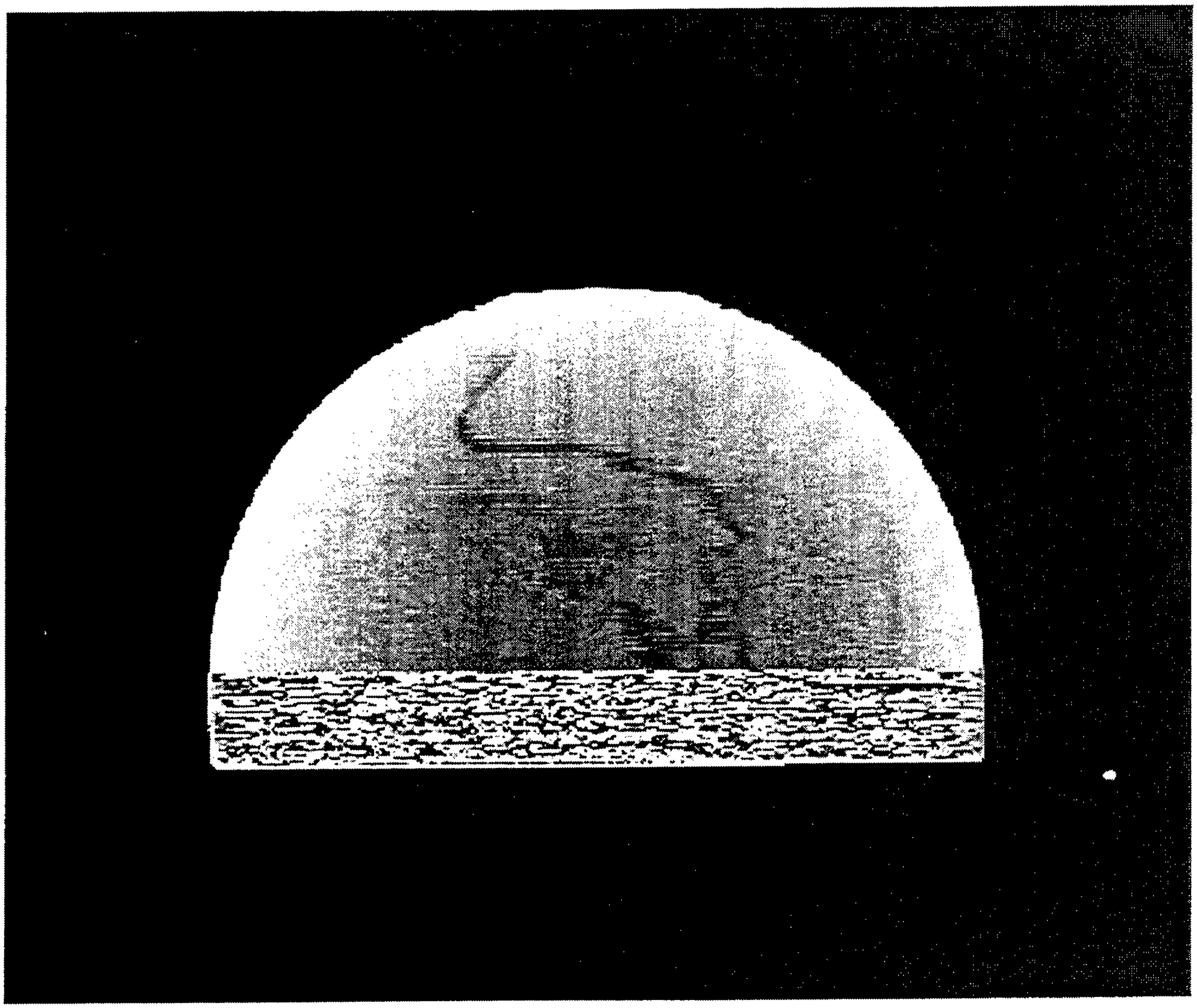

Figure A-32. 19.20 mm from bottom of disk with 65° rotation about X-axis.

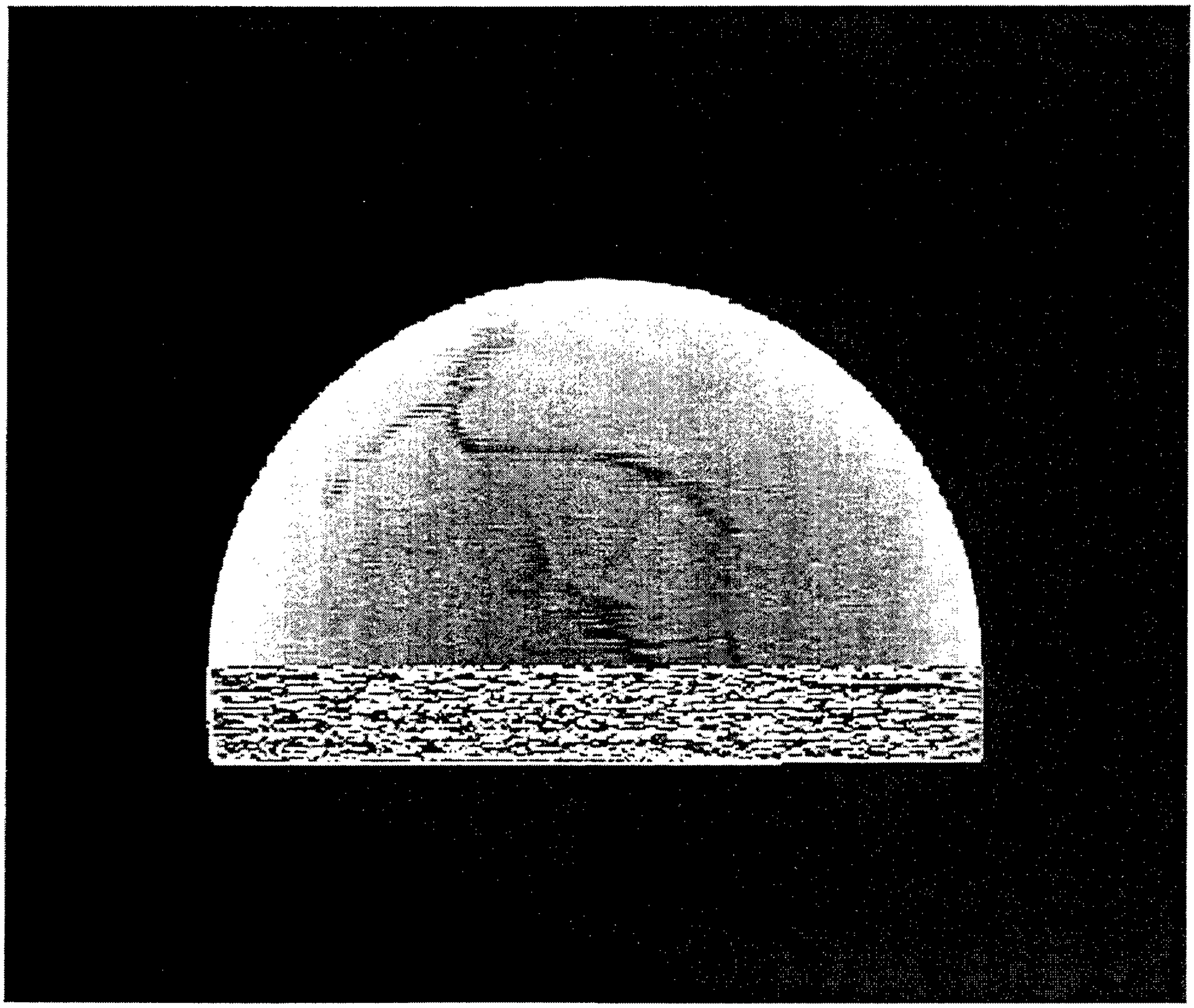

Figure A-33. 19.69 mm from bottom of disk with 65° rotation about X-axis.

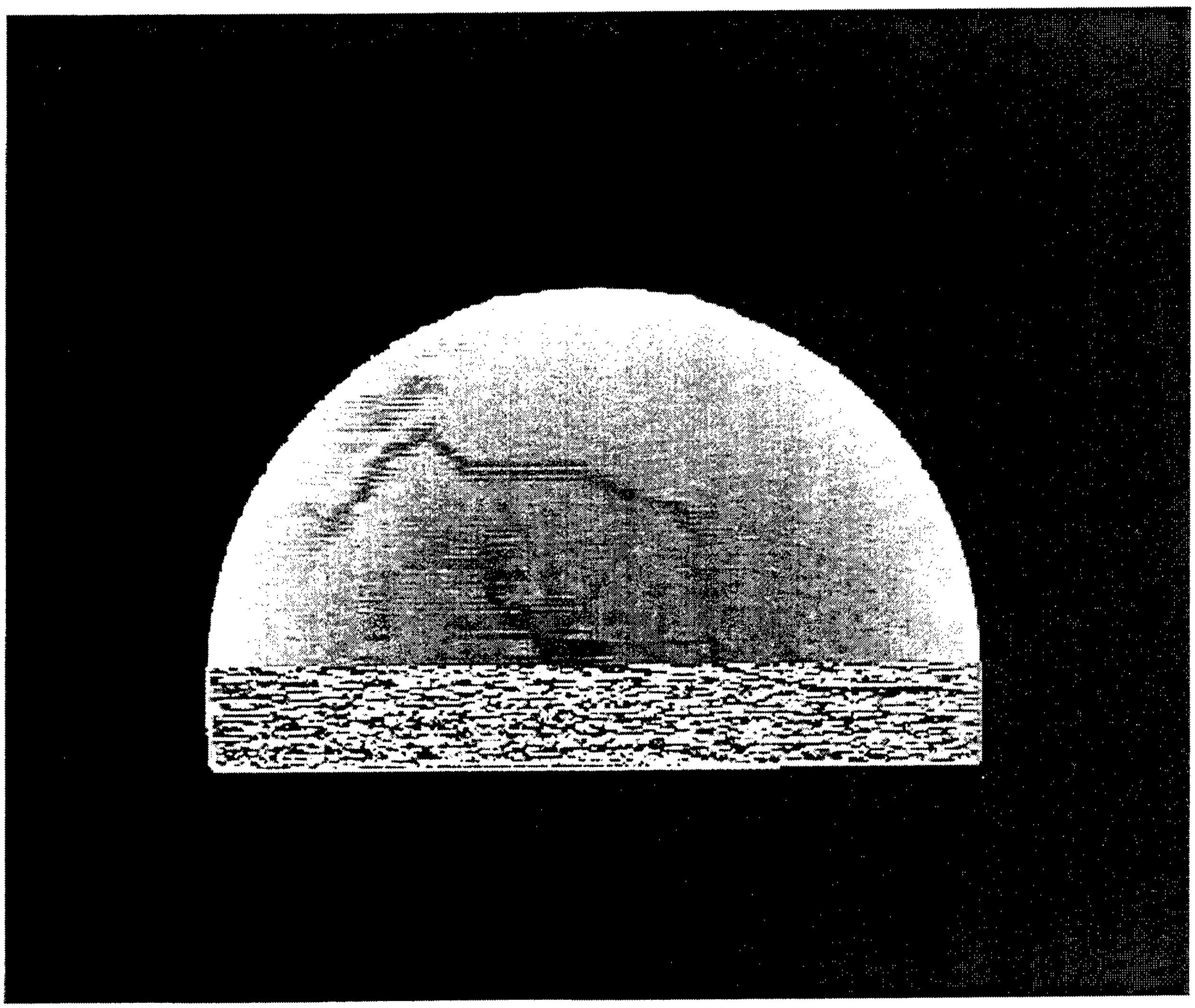

Figure A-34. 20.18 mm from bottom of disk with 65° rotation about X-axis.

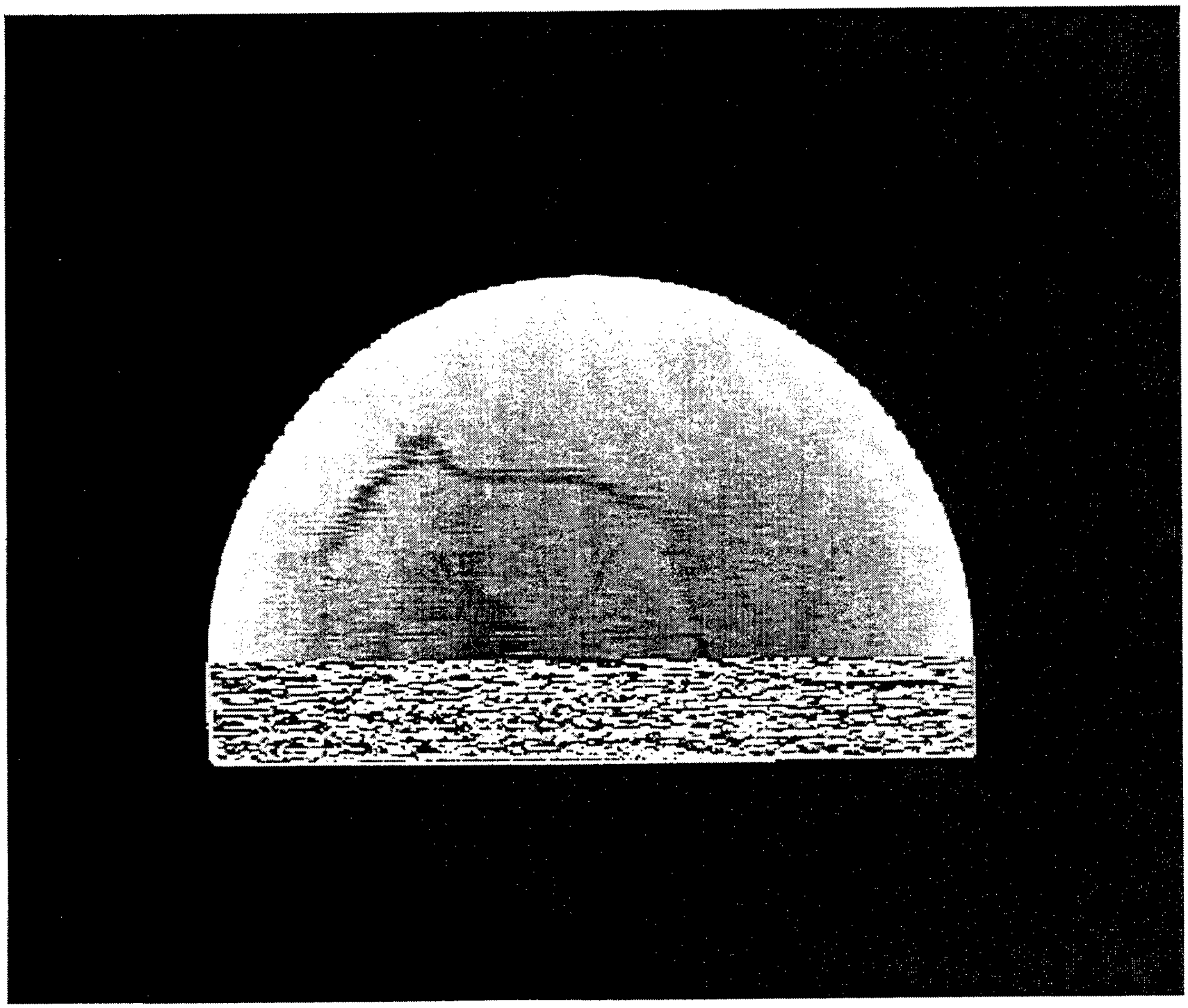

Figure A-35. 20.91 mm from bottom of disk with 65° rotation about X-axis.

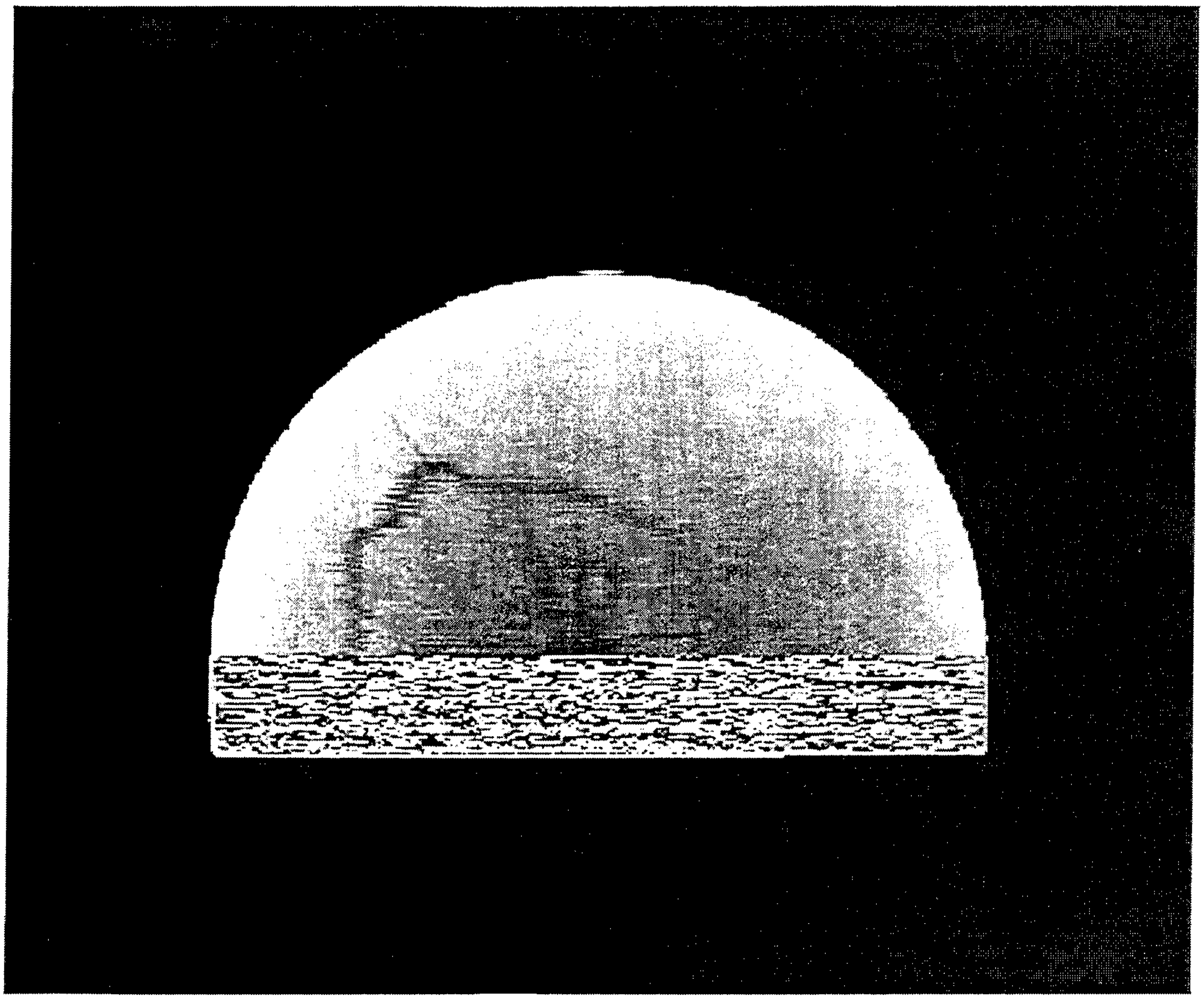

Figure A-36. 21.40 mm from bottom of disk with 65° rotation about X-axis.

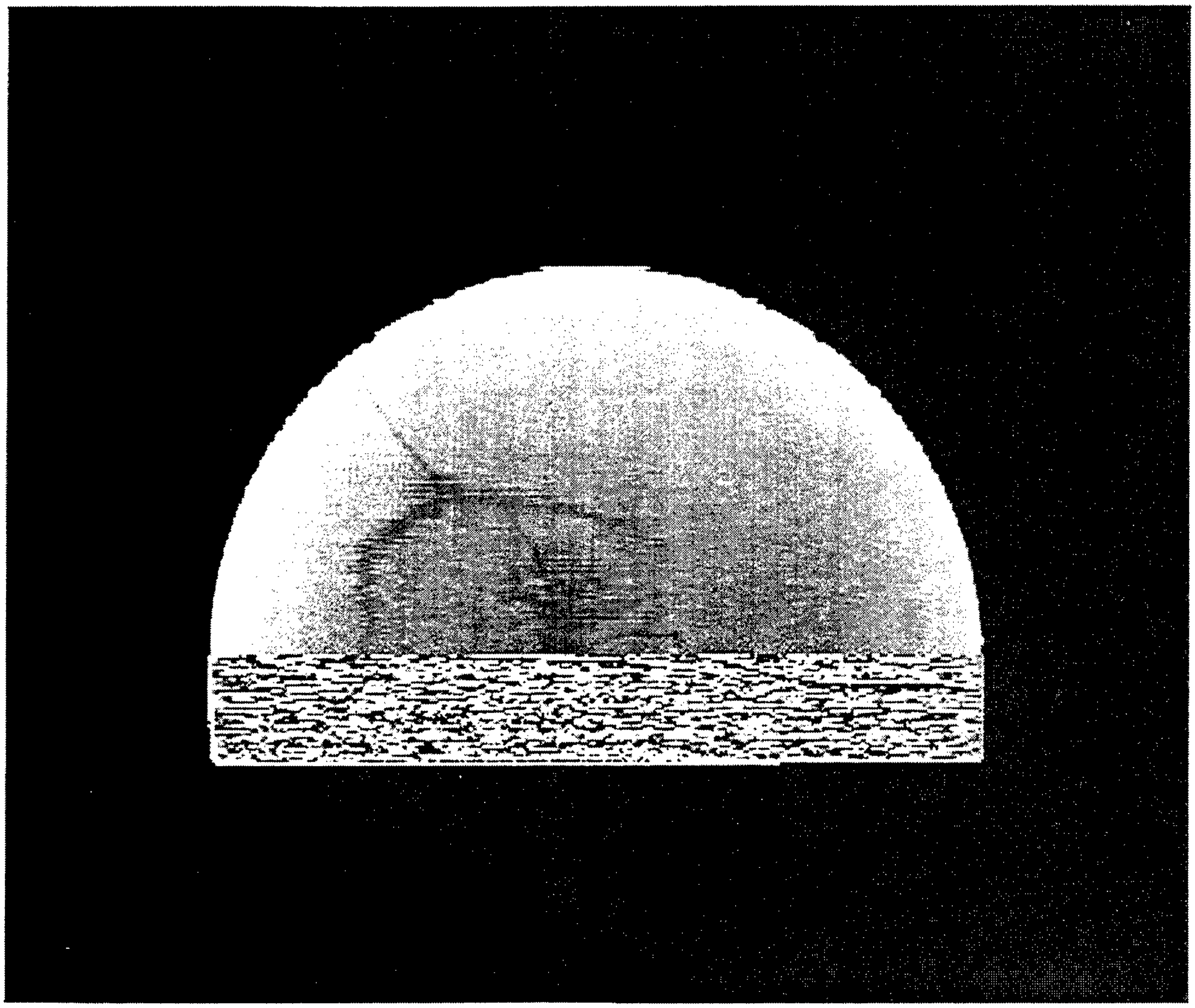

Figure A-37. 22.13 mm from bottom of disk with 65° rotation about X-axis.

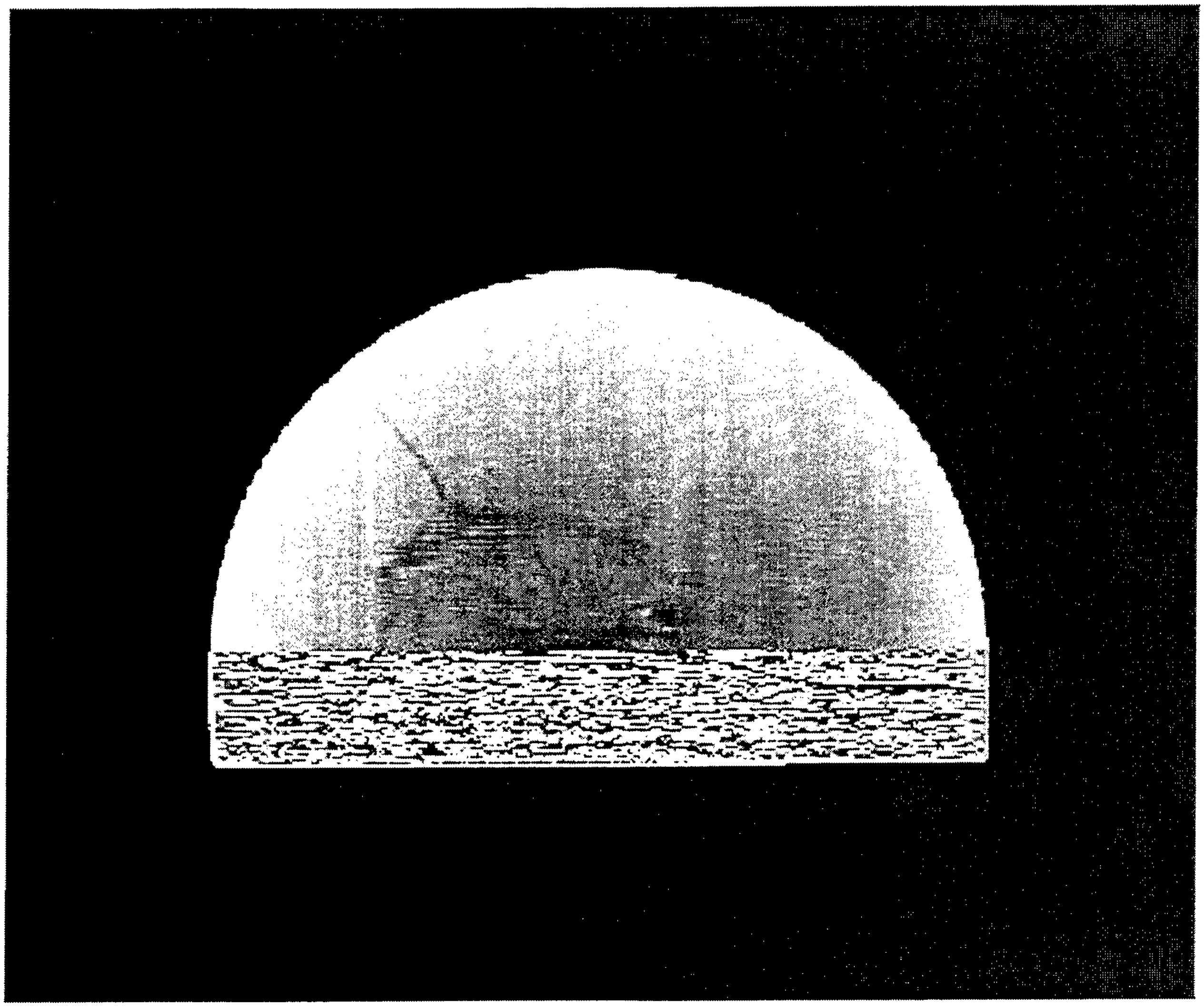

Figure A-38. 22.62 mm from bottom of disk with 65° rotation about X-axis.

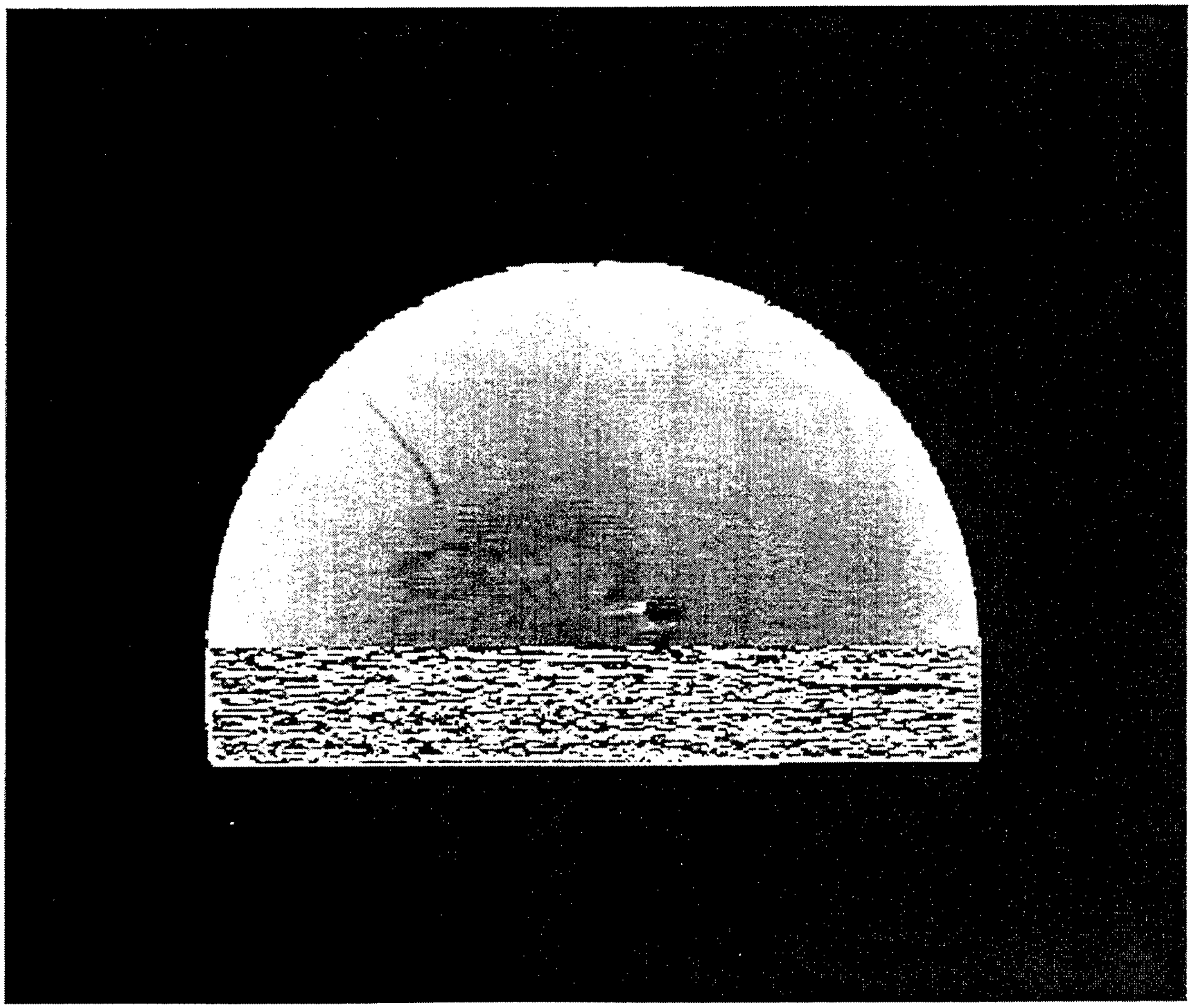

Figure A-39. 23.35 mm from bottom of disk with 65° rotation about X-axis.

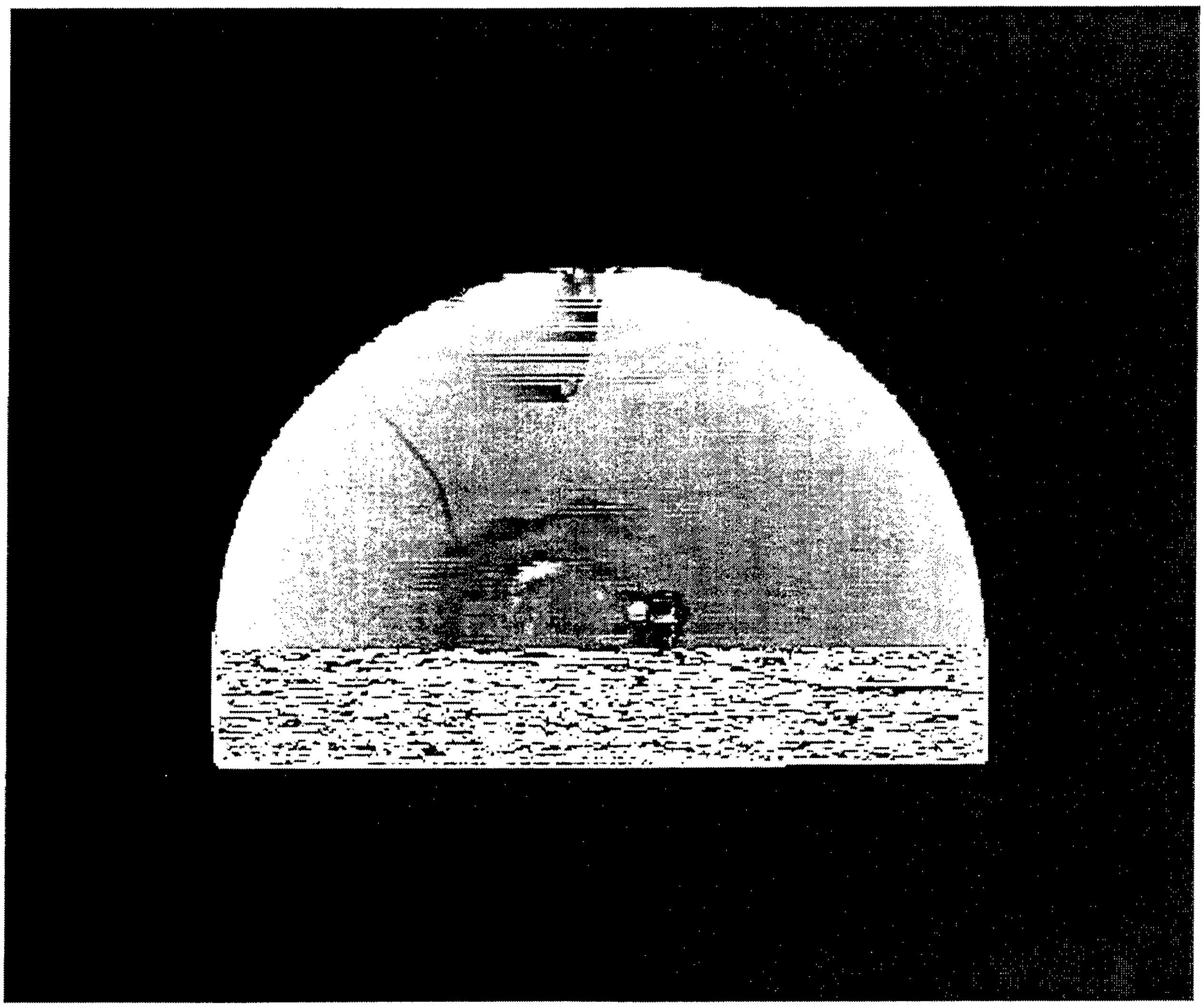

Figure A-40. 23.84 mm from bottom of disk with 65° rotation about X-axis.

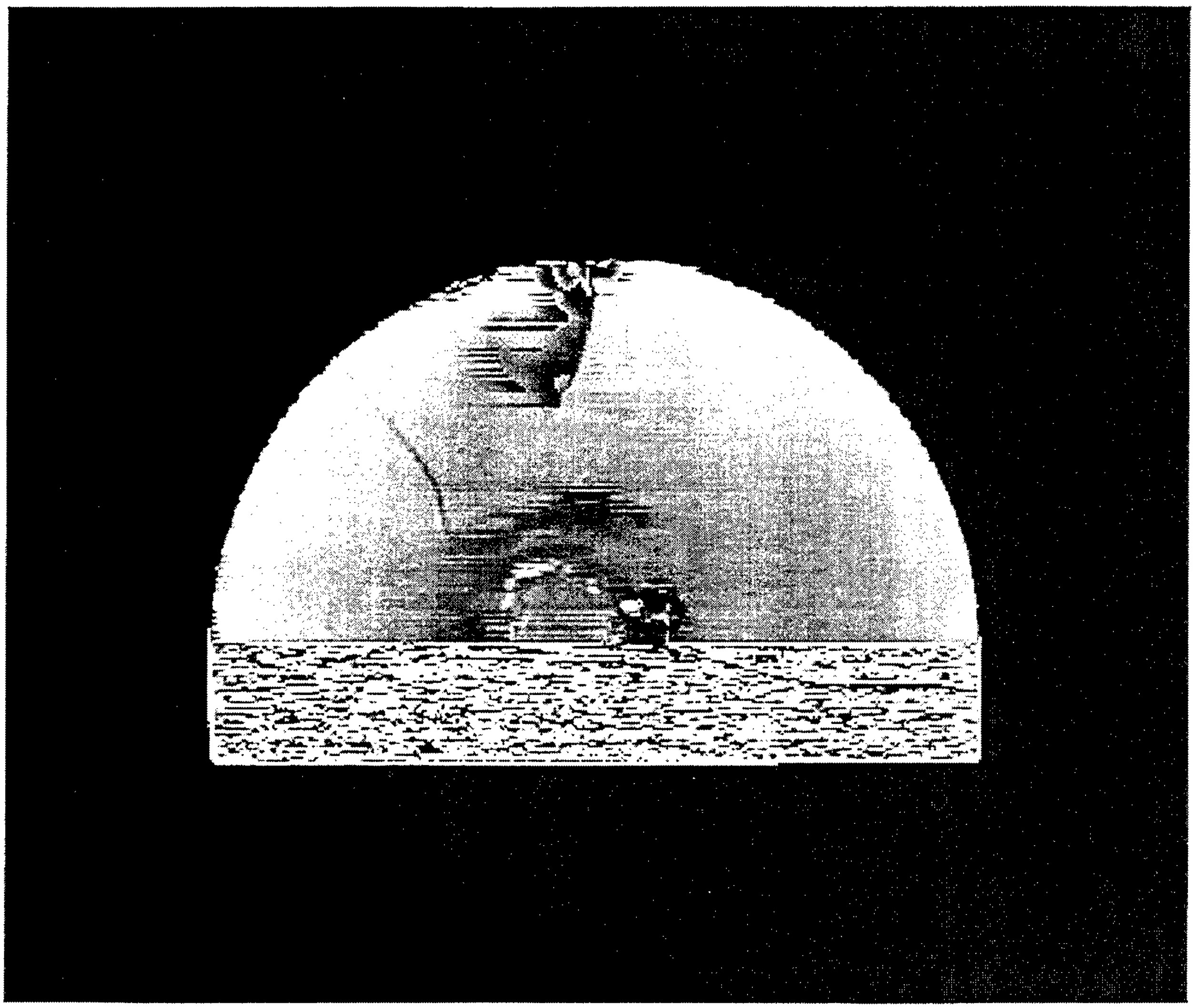

Figure A-41. 24.33 mm from bottom of disk with 65° rotation about X-axis.

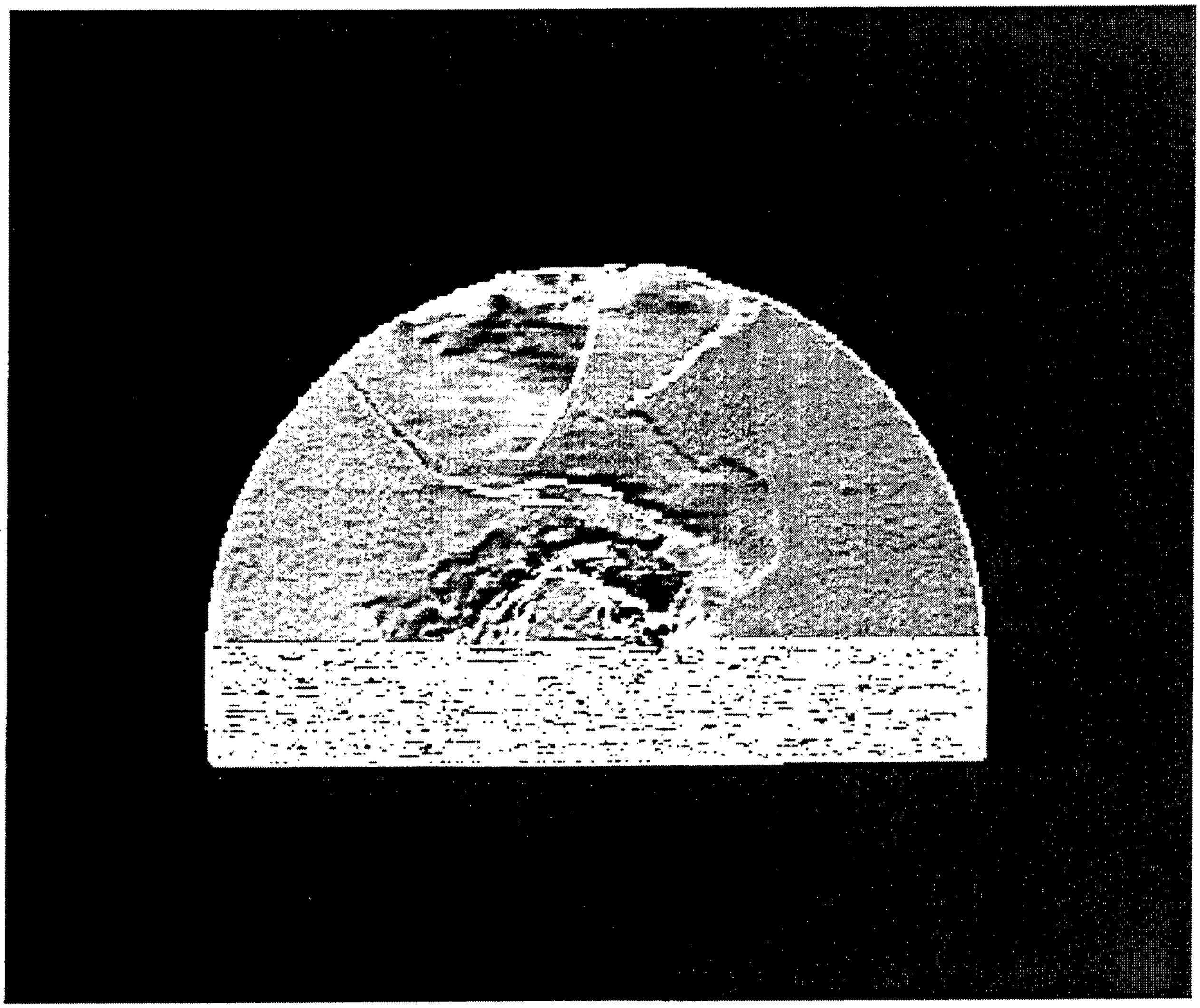

Figure A-42. 24.57 mm from bottom of disk with 65° rotation about X-axis.

Appendix B. Point Clouds of Titanium Carbide (TiC) Sample

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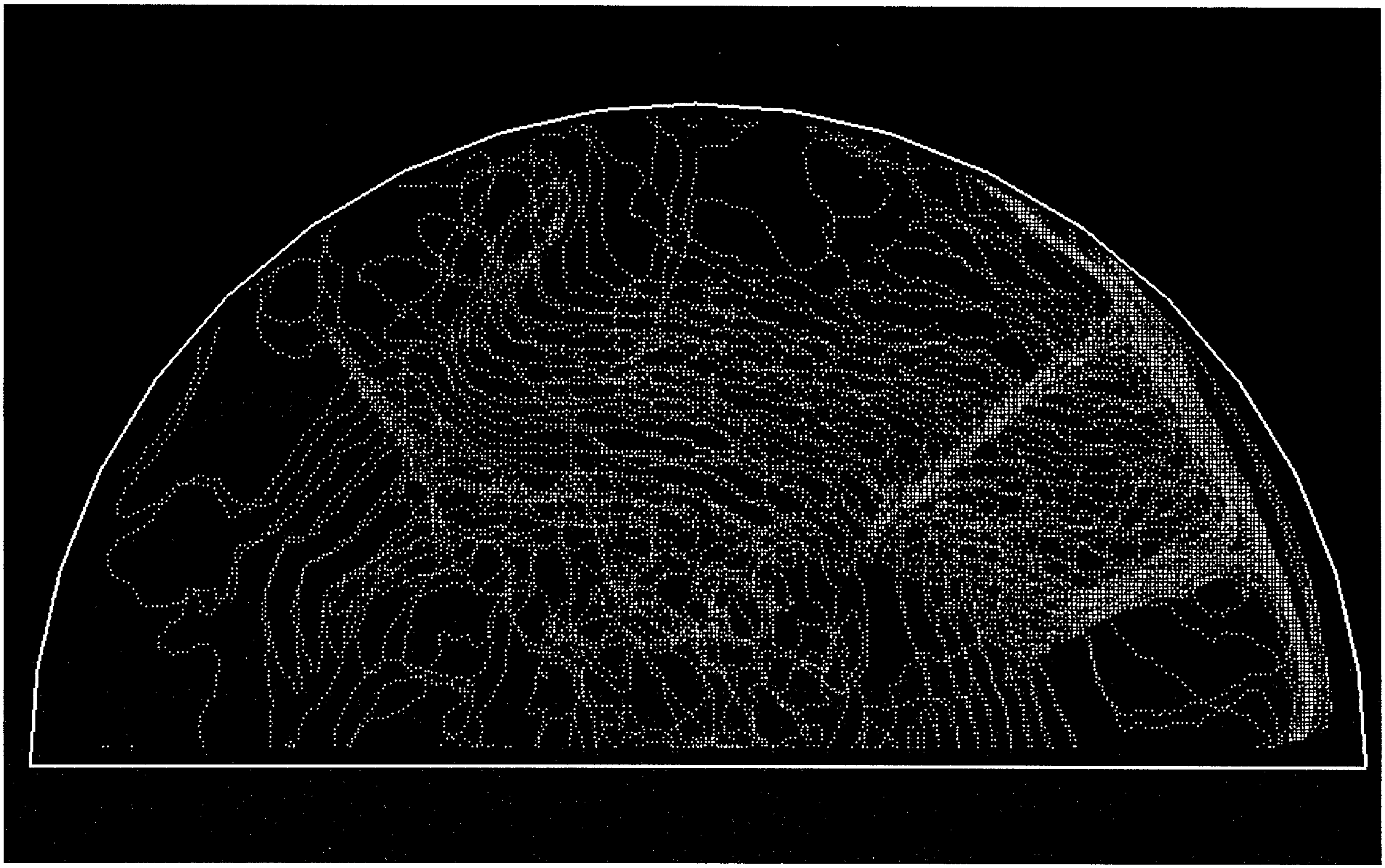

Figure B-1. 0° rotation about X-axis.

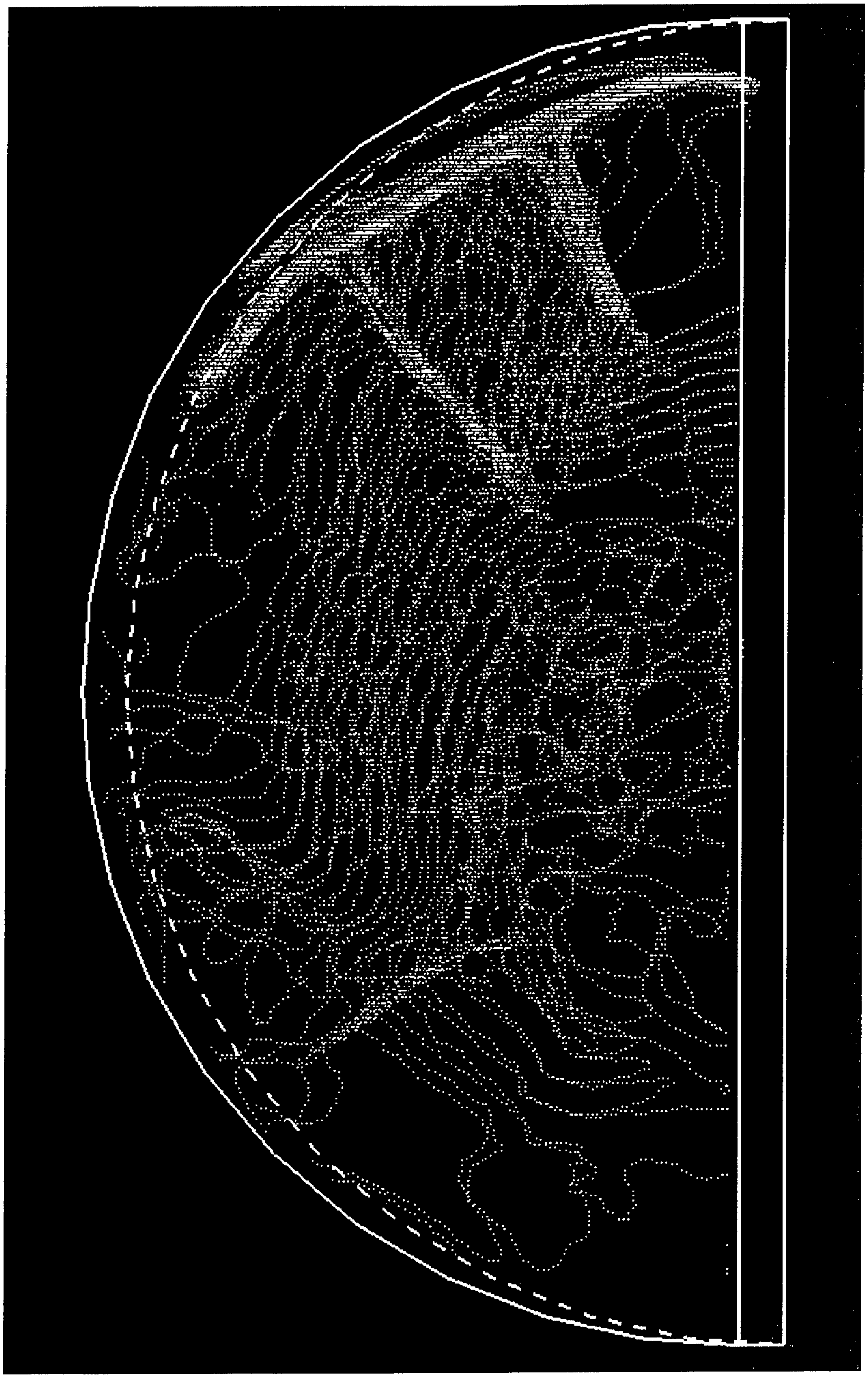

Figure B-2. 5° rotation about X-axis.

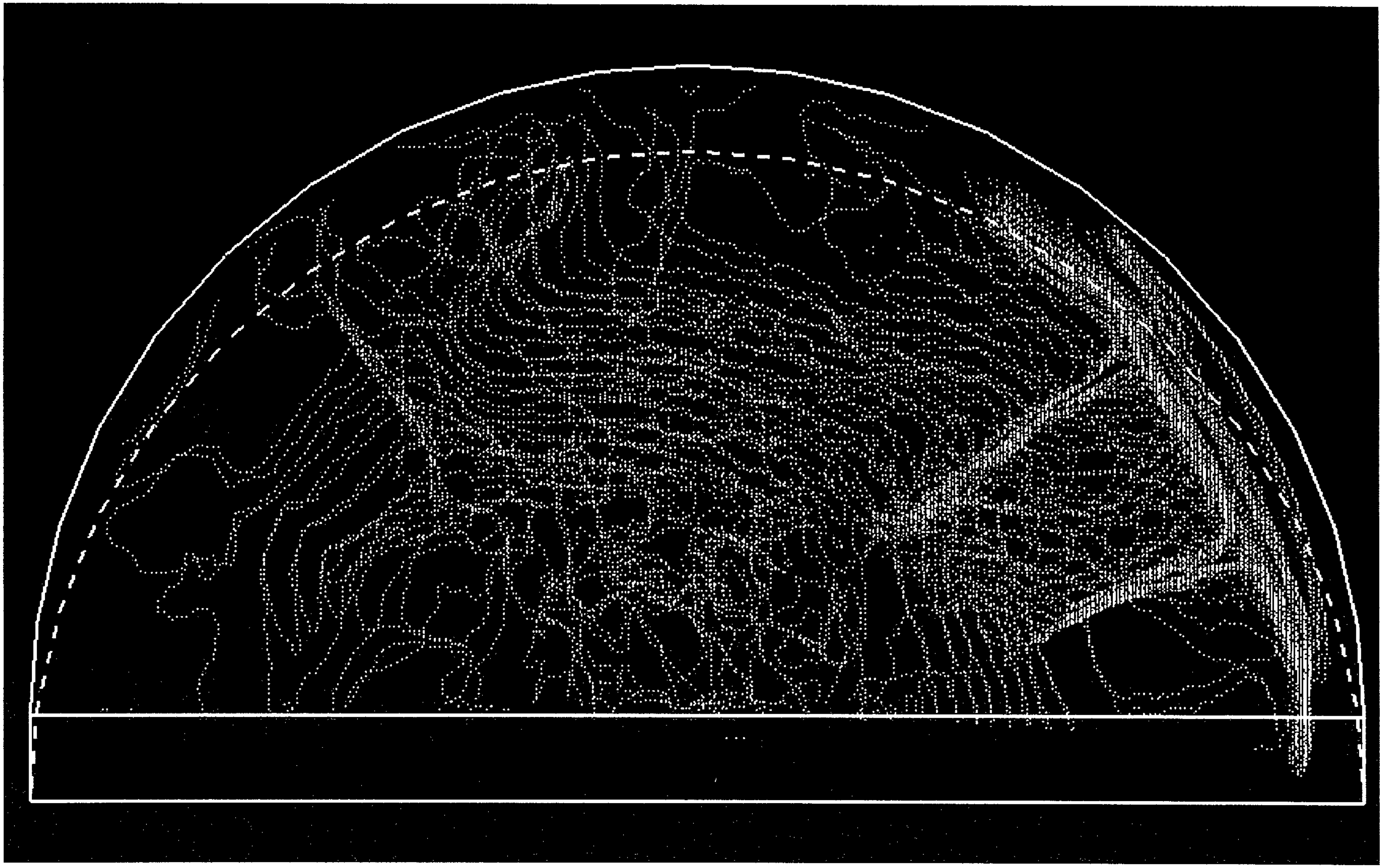

Figure B-3. 10° rotation about X-axis.

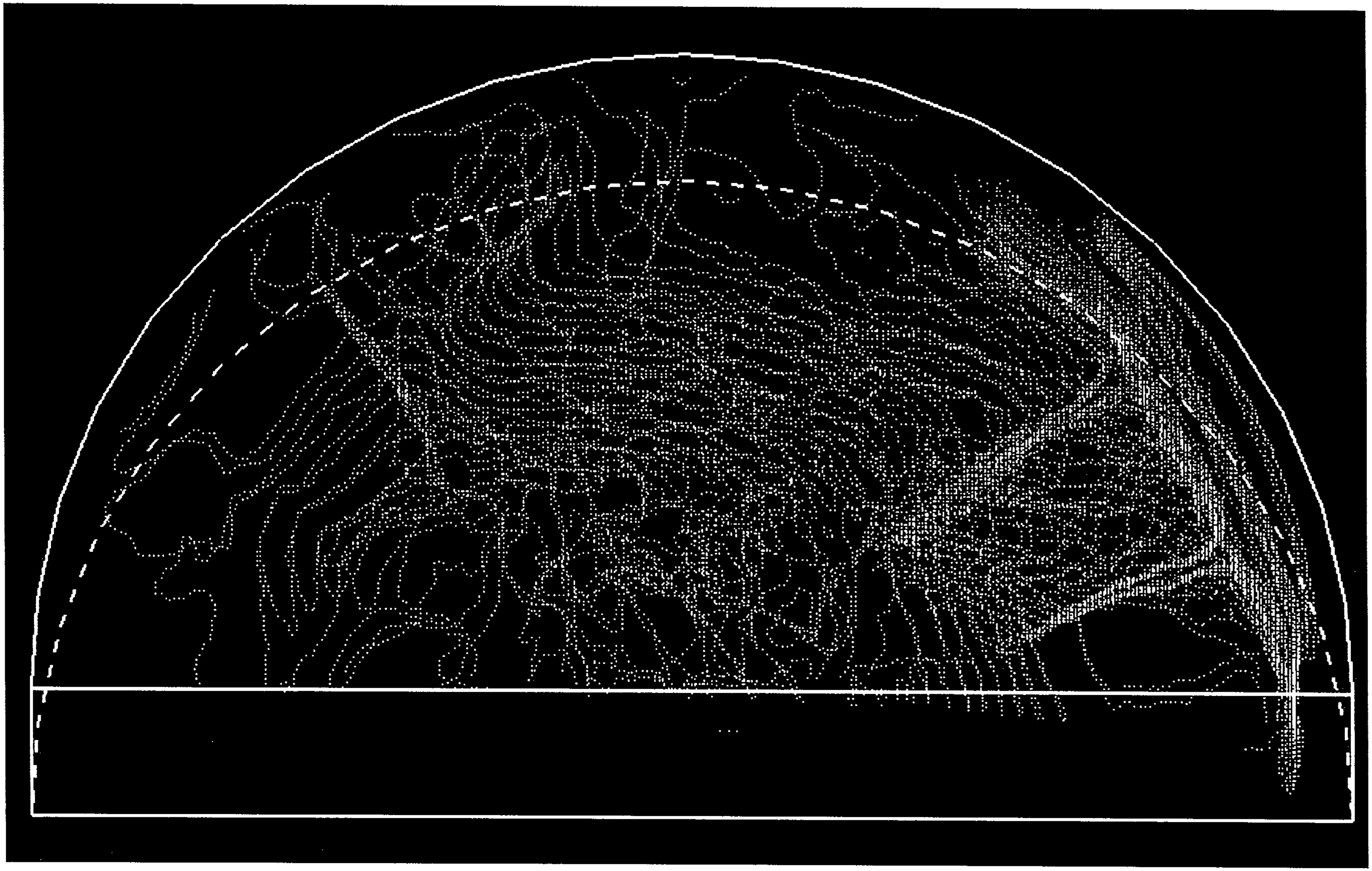

Figure B-4. 15° rotation about X-axis.

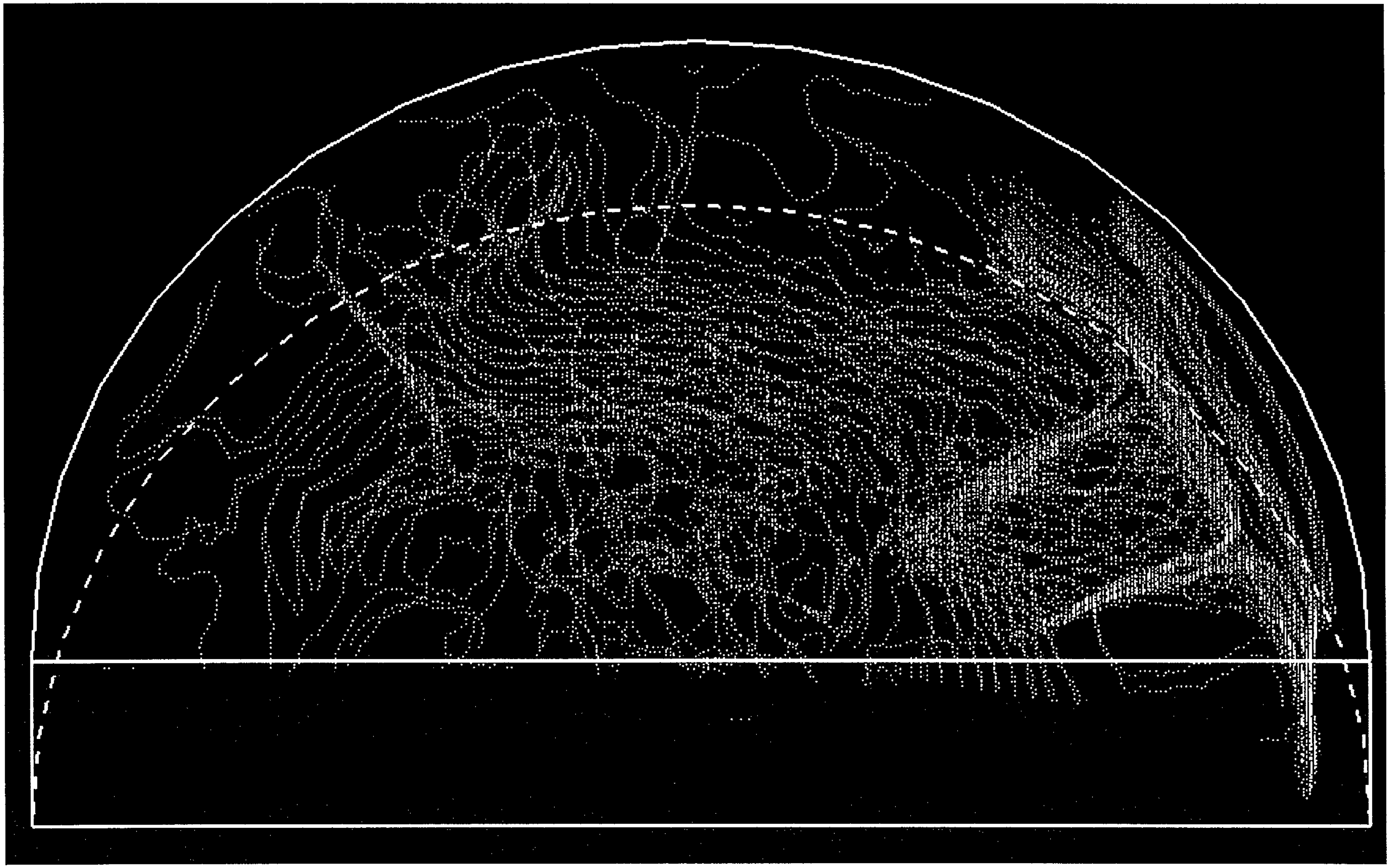

Figure B-5. 20° rotation about X-axis.

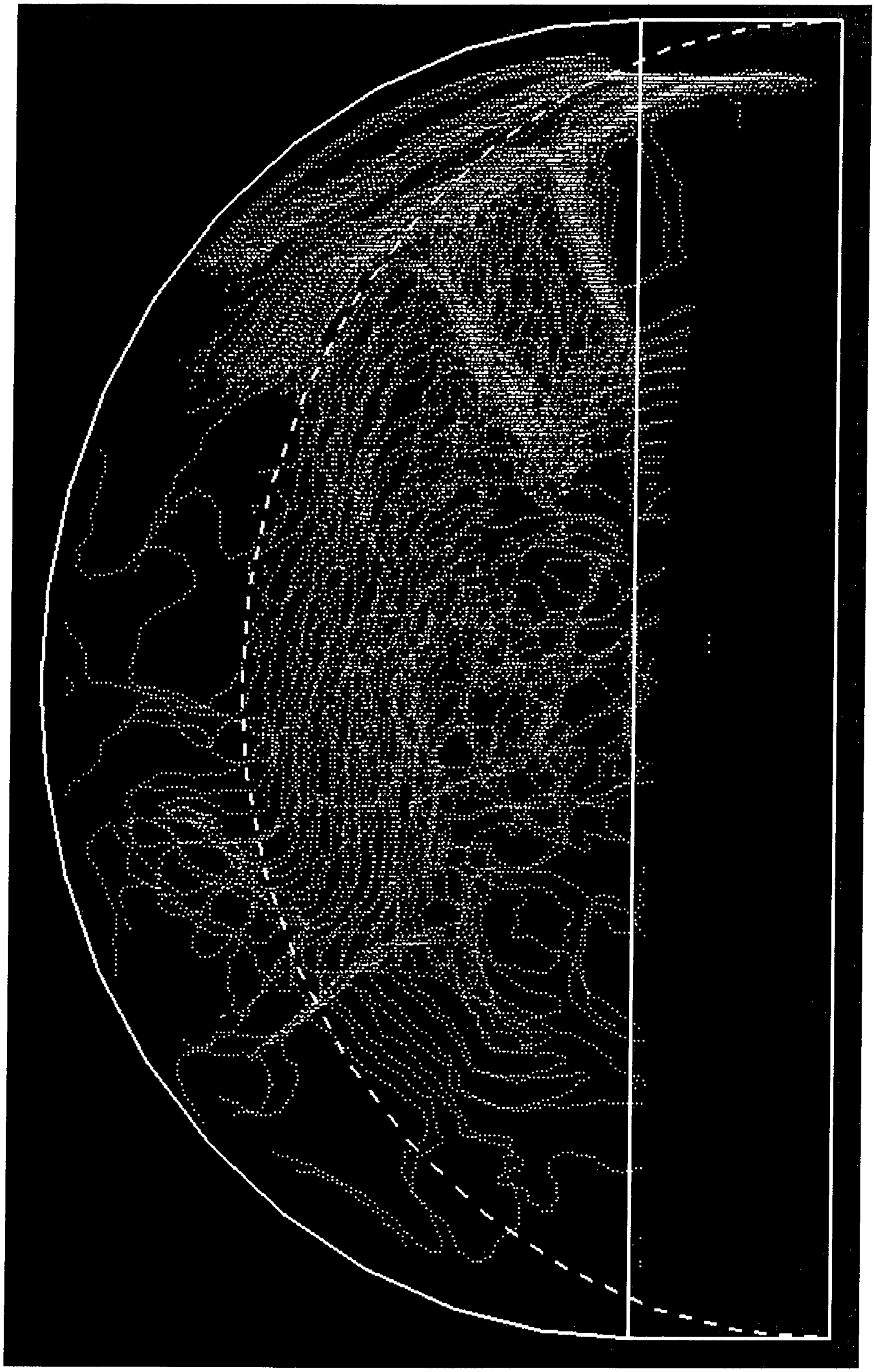

Figure B-6. 25° rotation about X-axis.

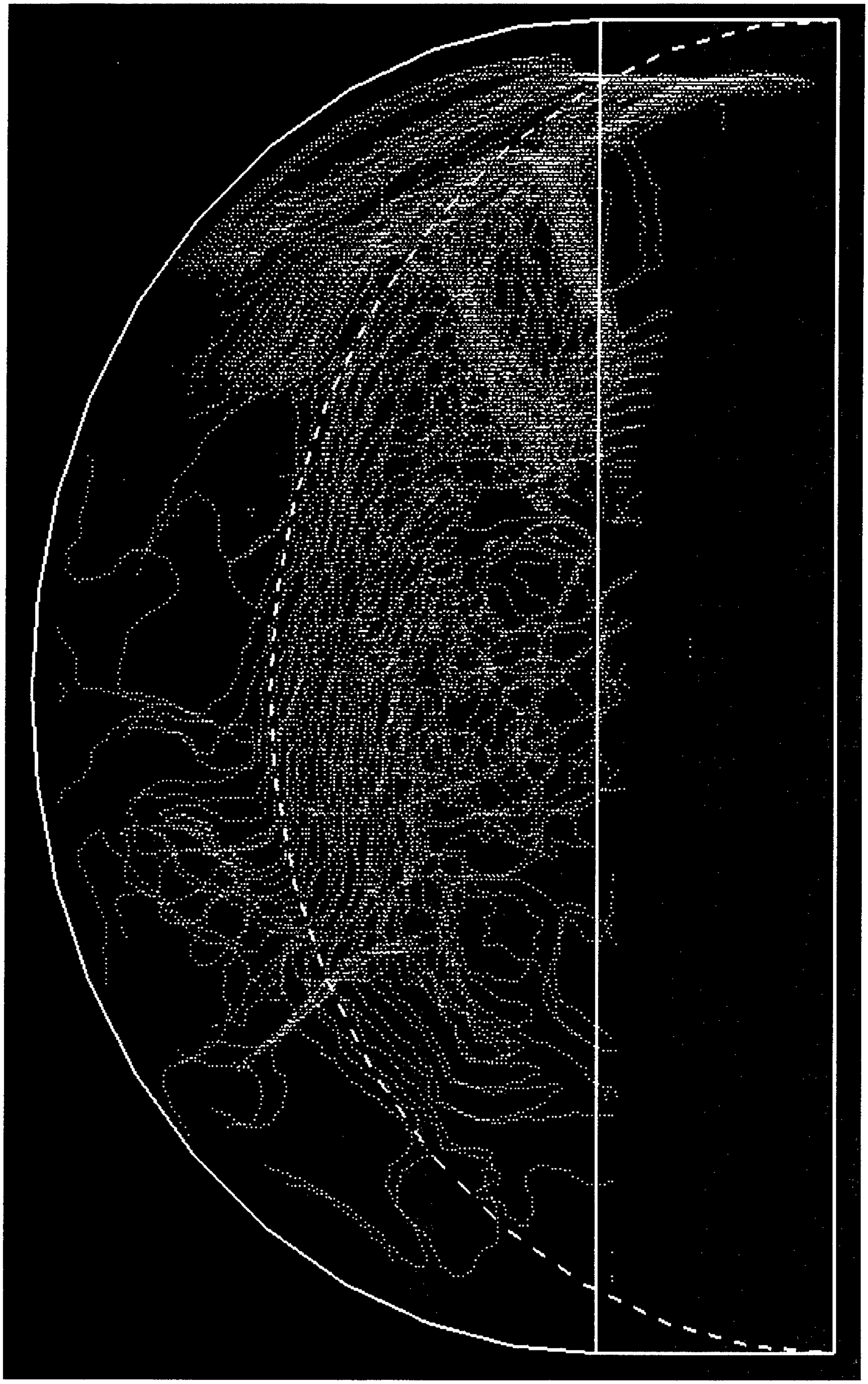

Figure B-7. 30° rotation about X-axis.

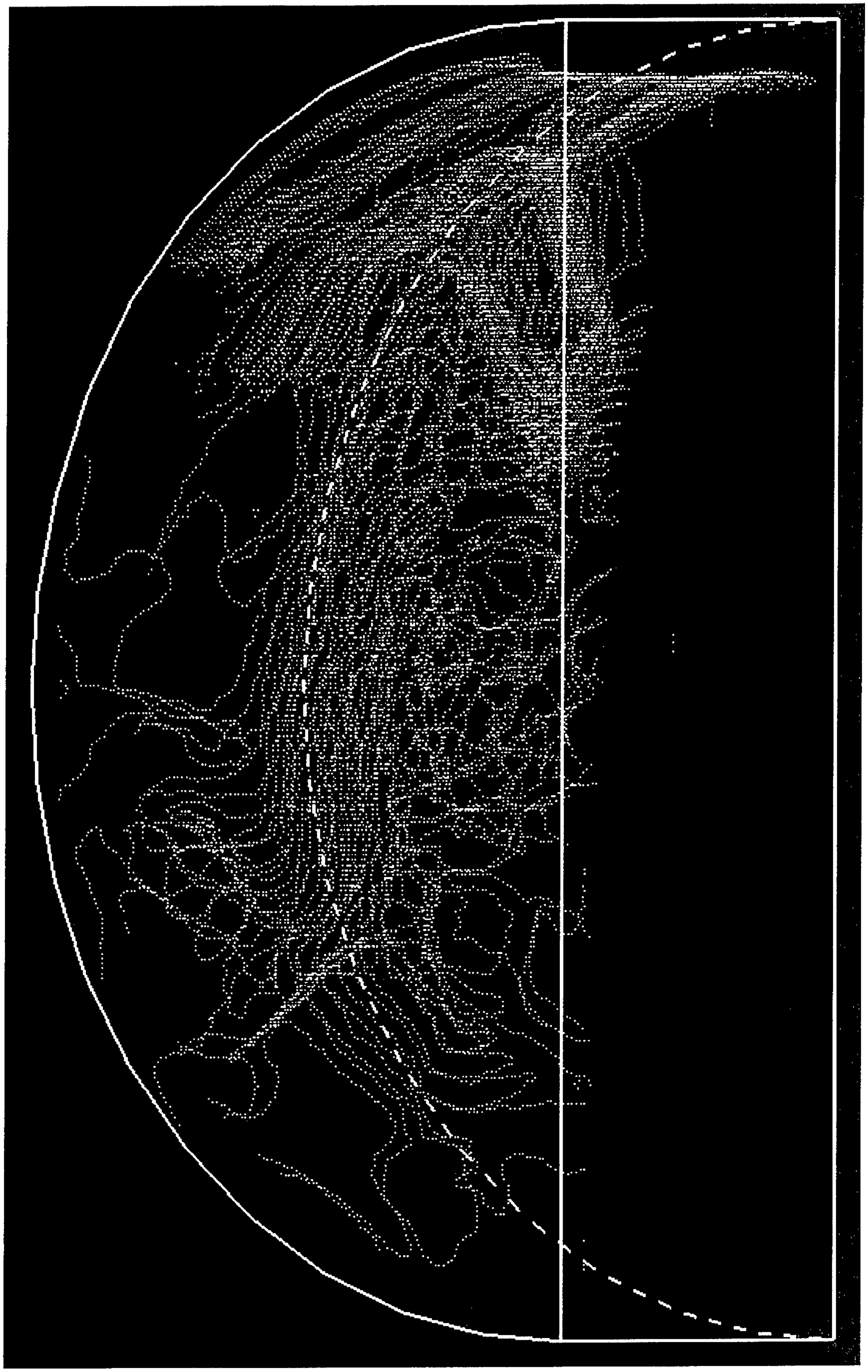

Figure B-8. 35° rotation about X-axis.

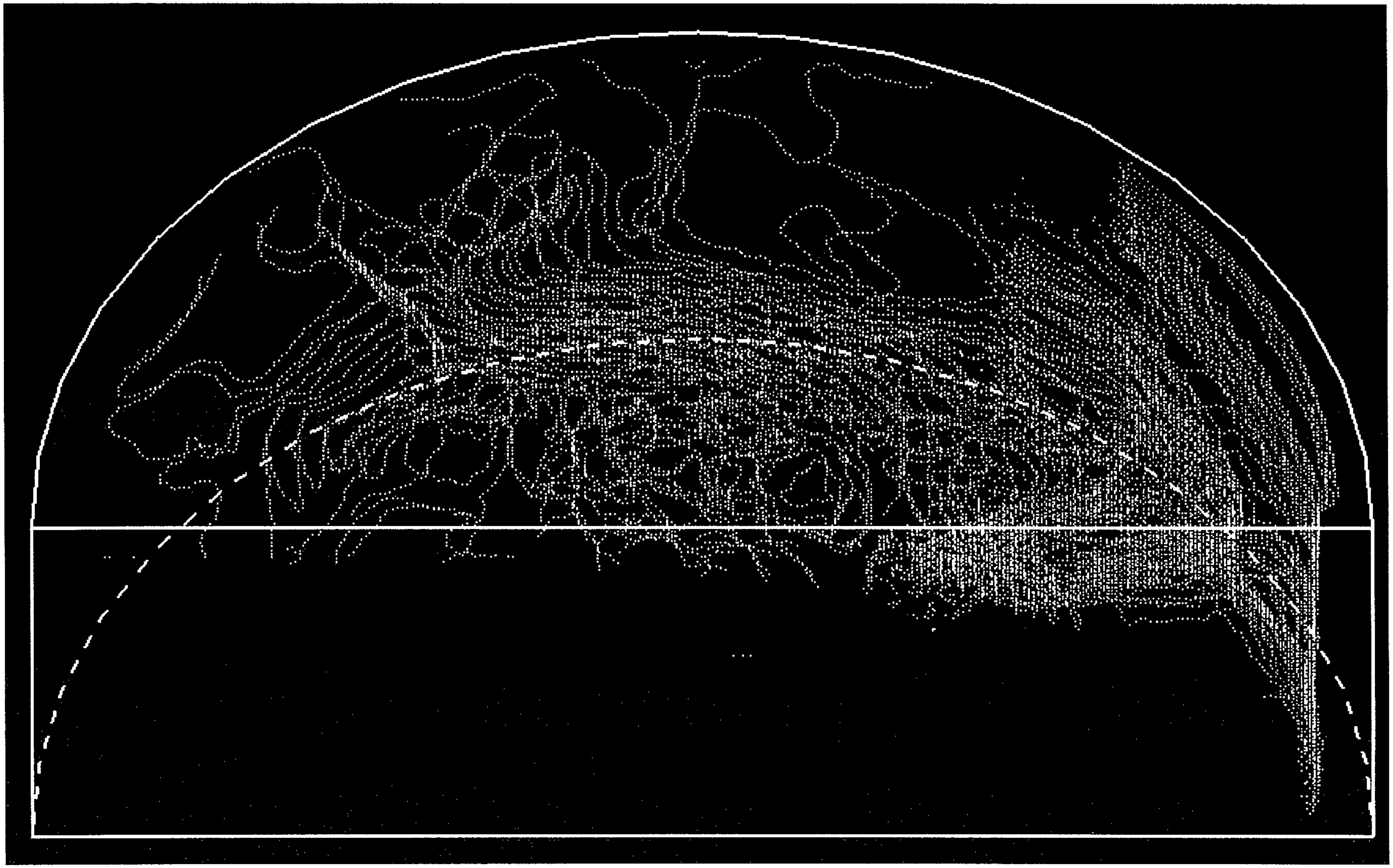

Figure B-9. 40° rotation about X-axis.

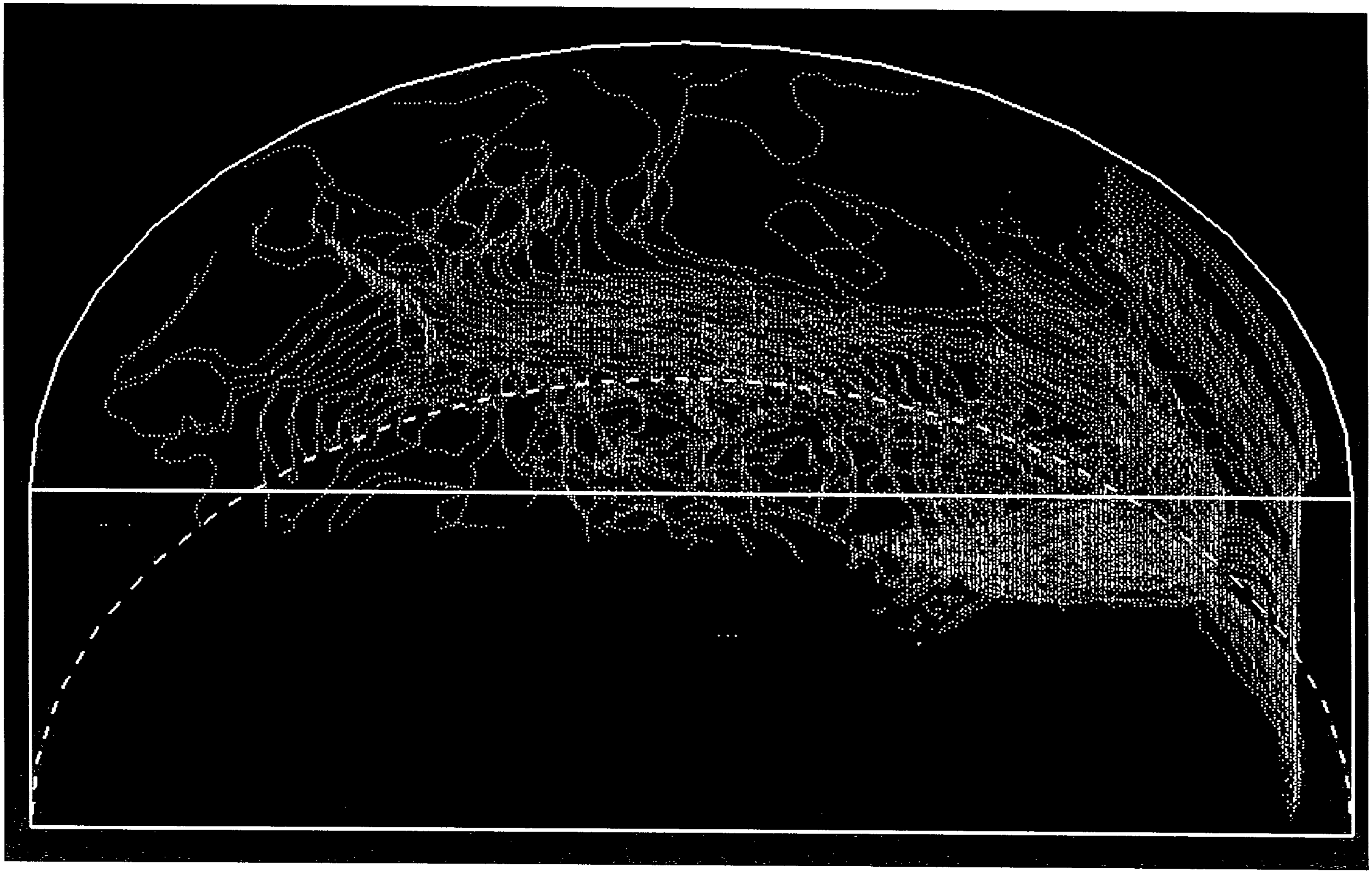

Figure B-10. 45° rotation about X-axis.

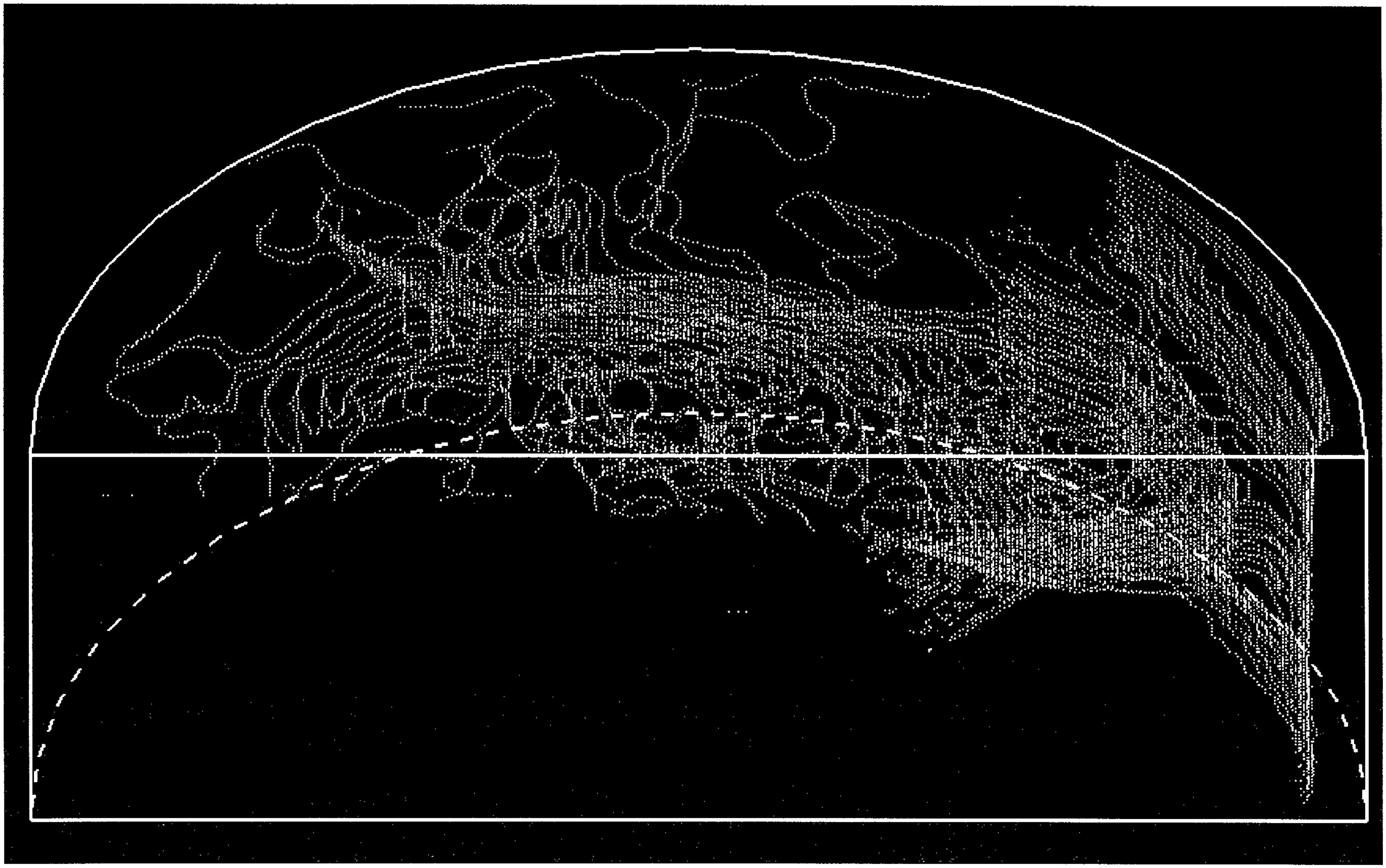

Figure B-11. 50° rotation about X-axis.

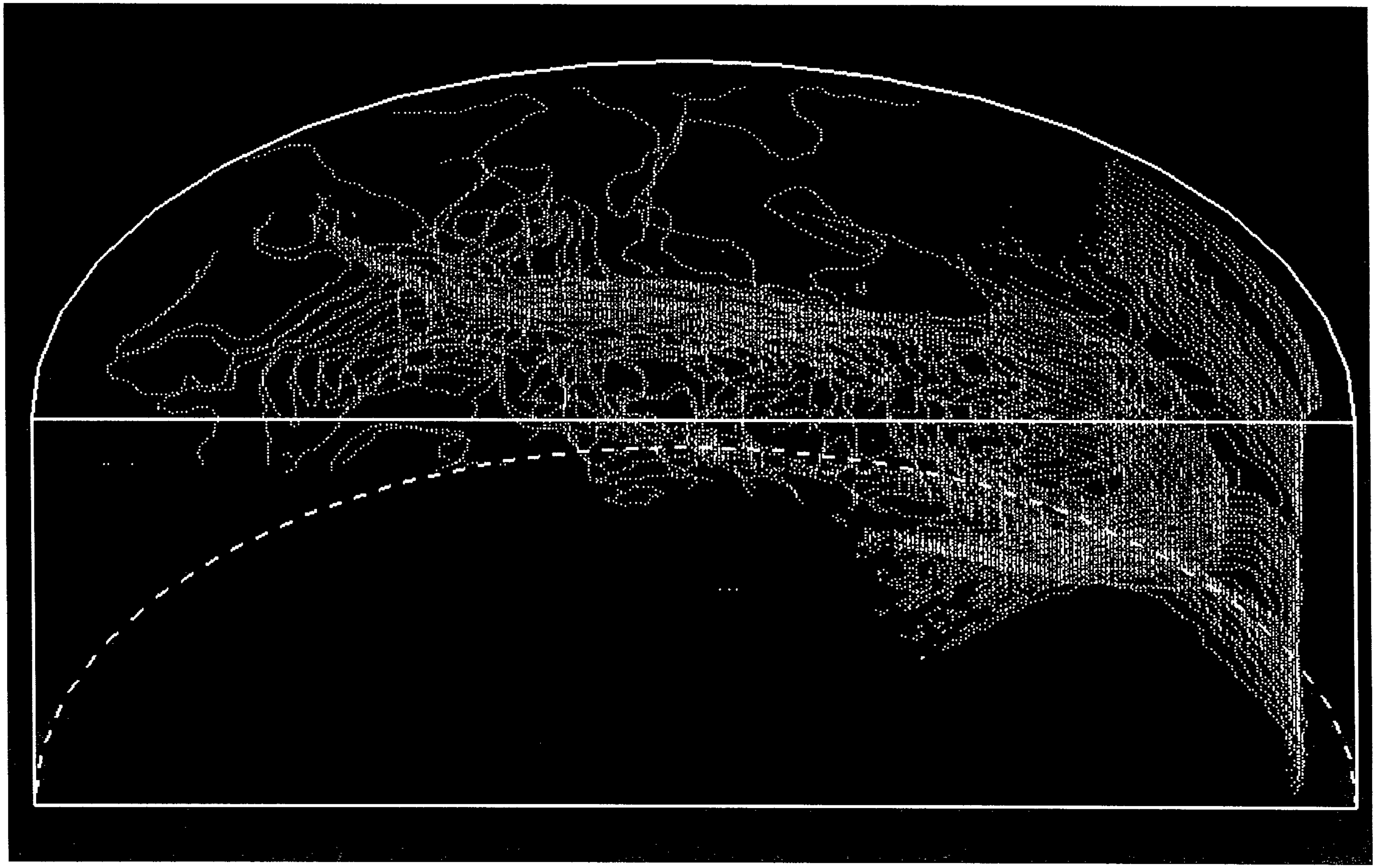

Figure B-12. 55° rotation about X-axis.

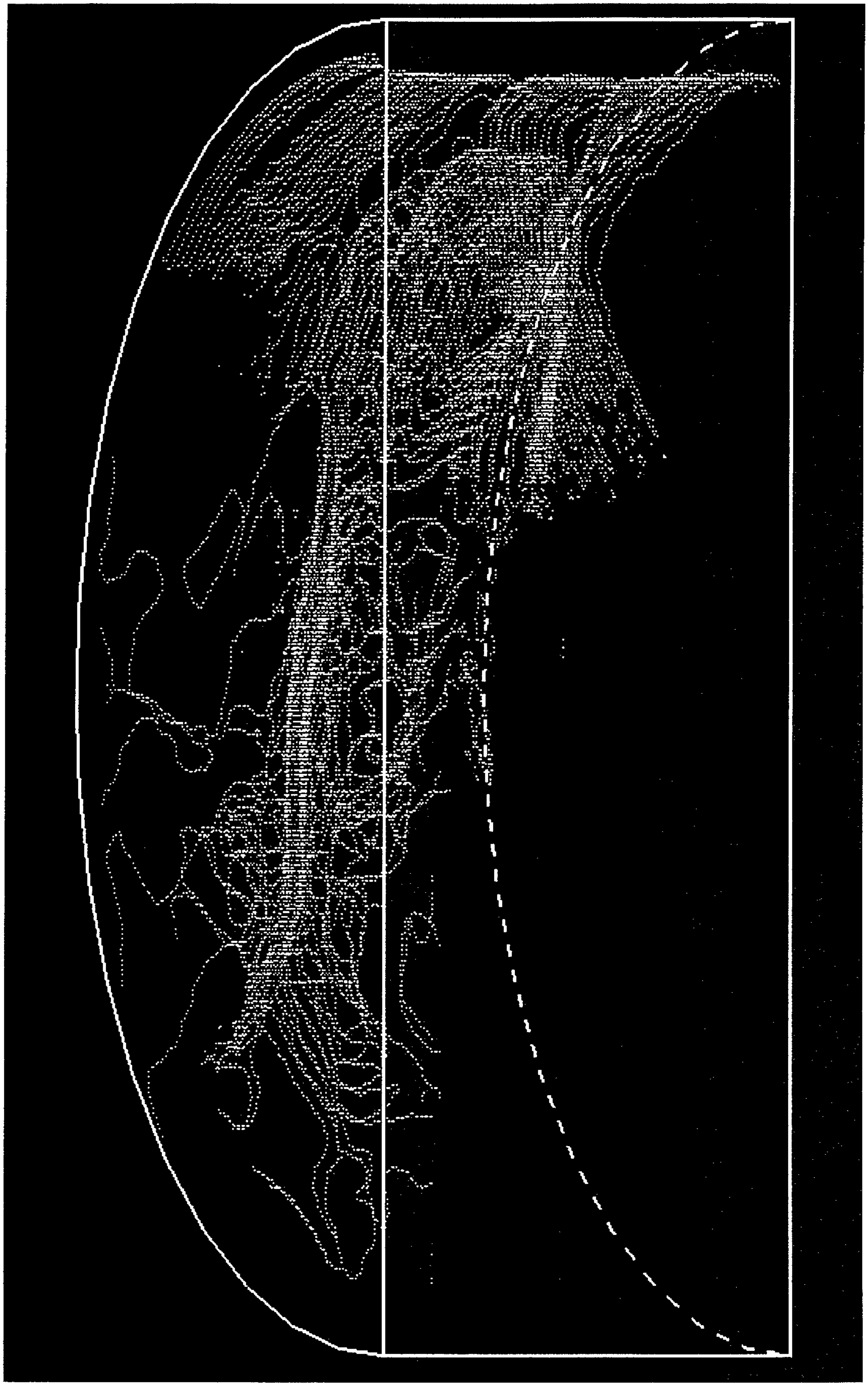

Figure B-13. 60° rotation about X-axis.

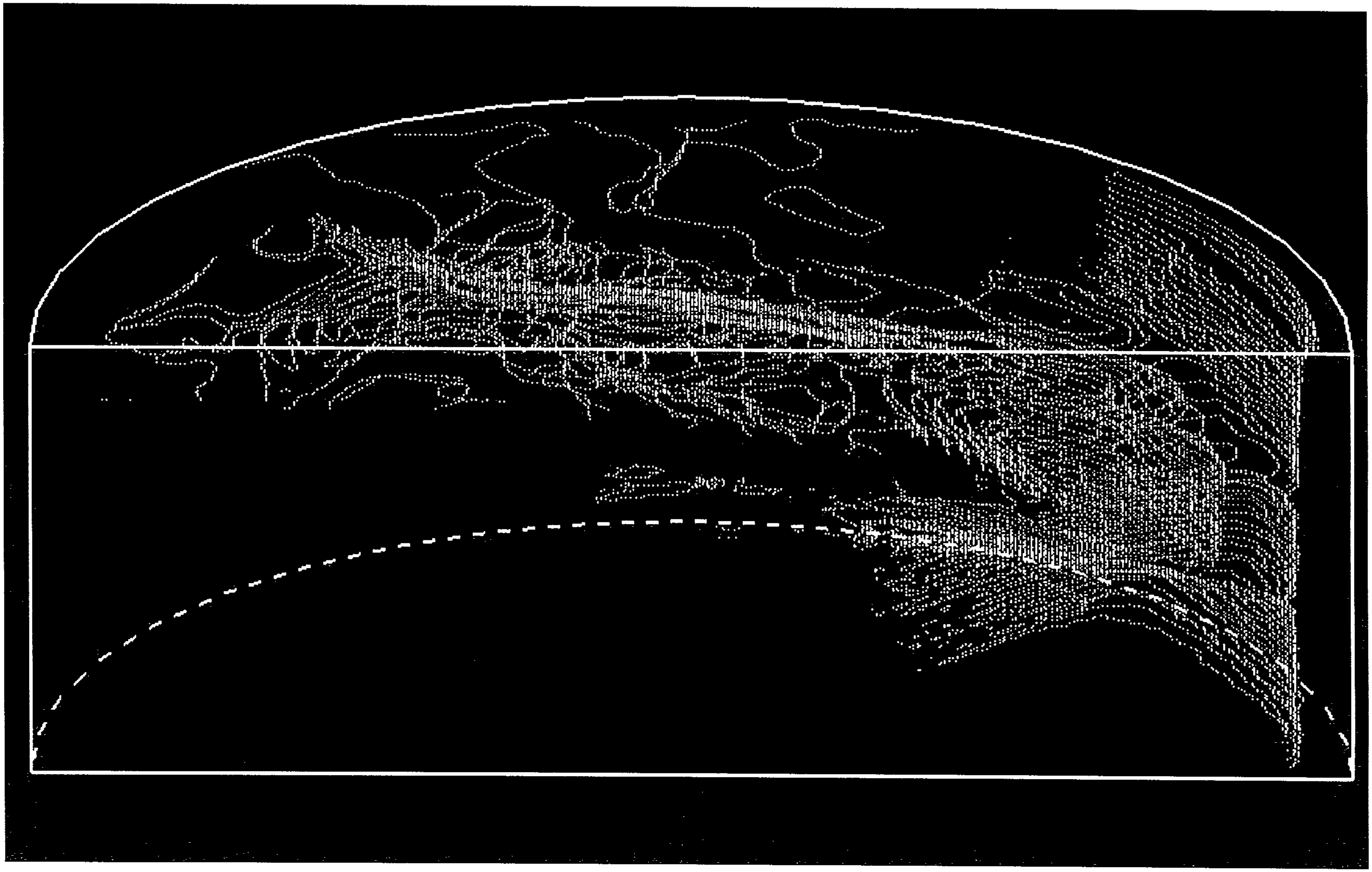

Figure B-14. 65° rotation about X-axis.

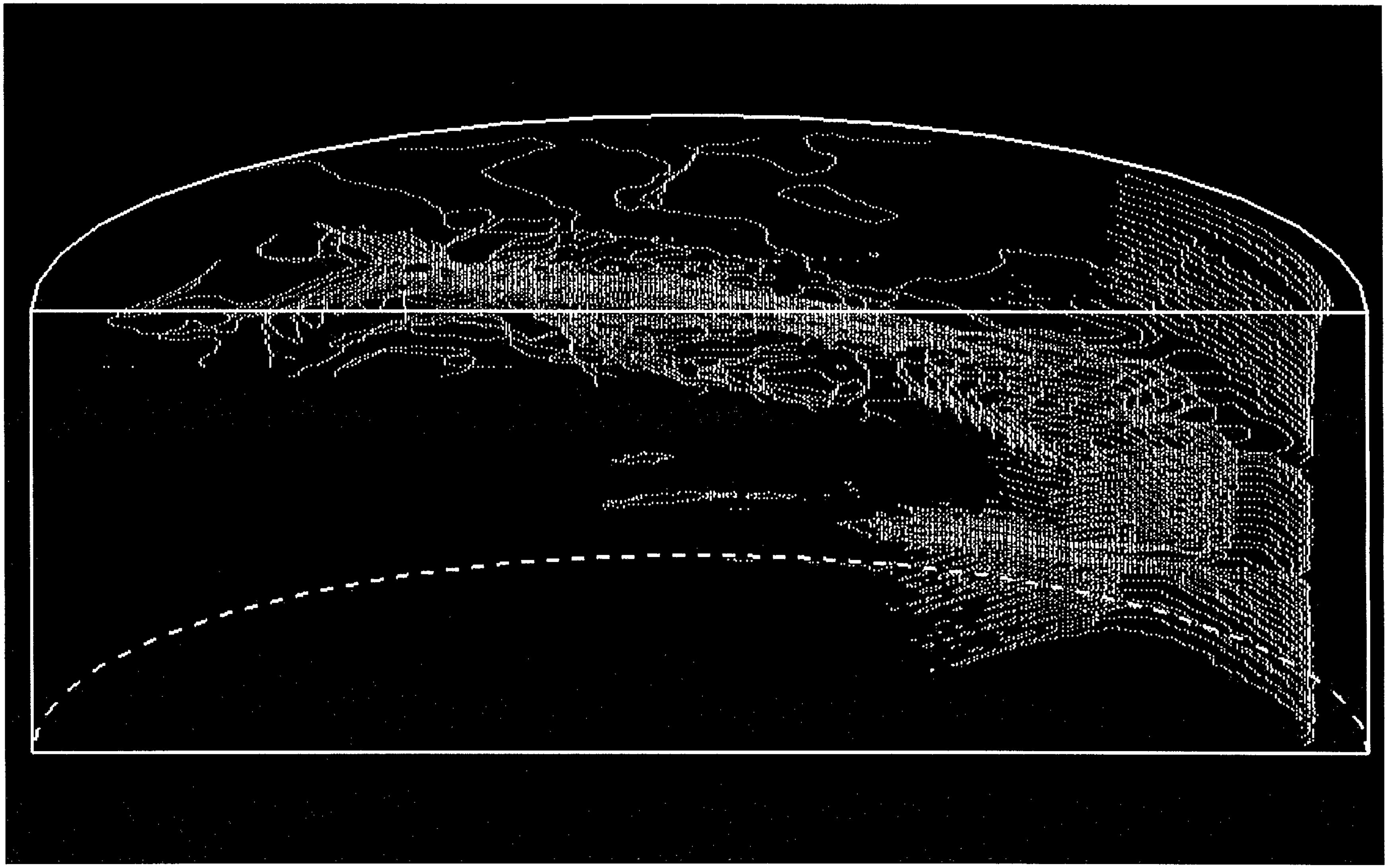

Figure B-15. 70° rotation about X-axis.

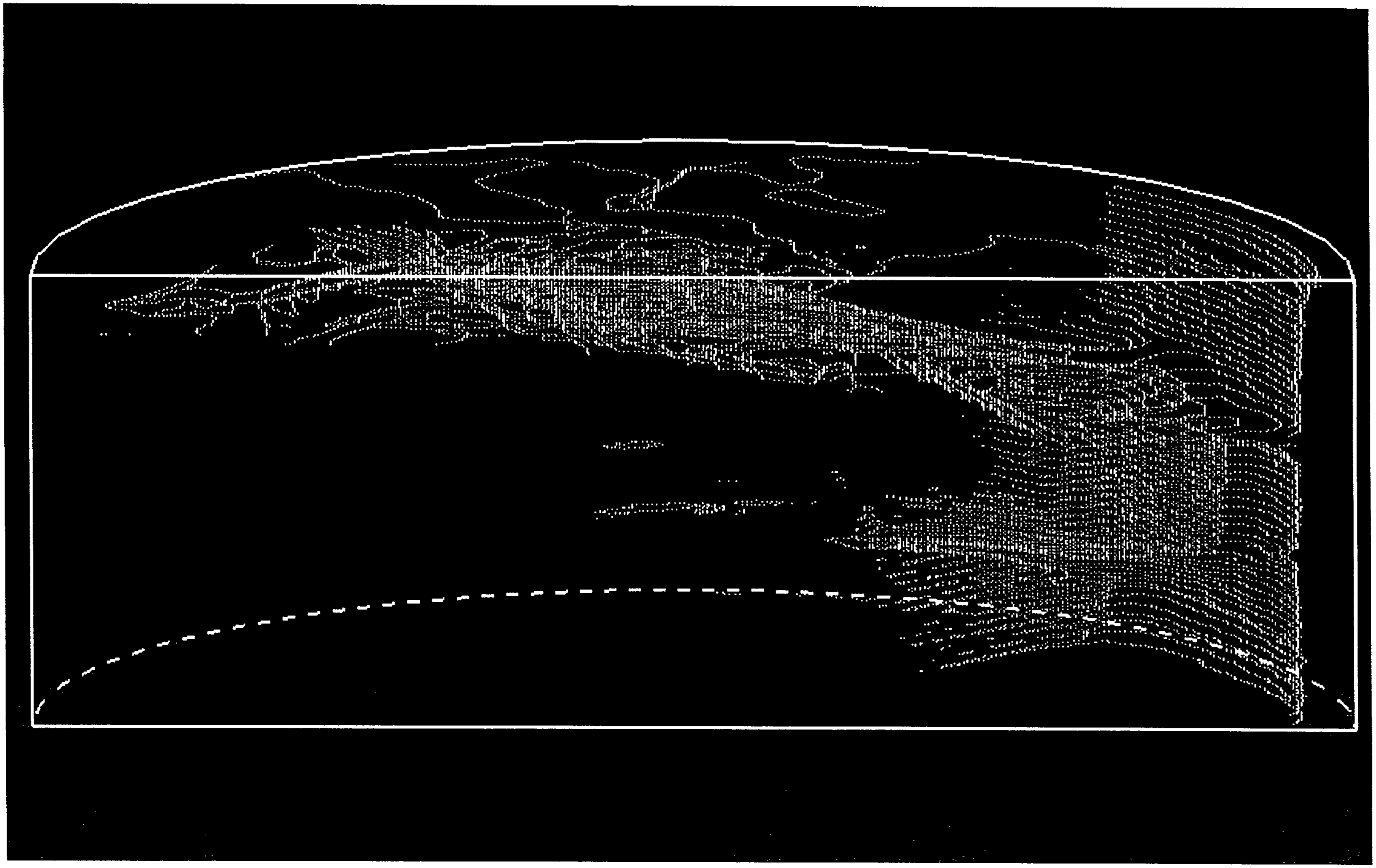

Figure B-16. 75° rotation about X-axis.

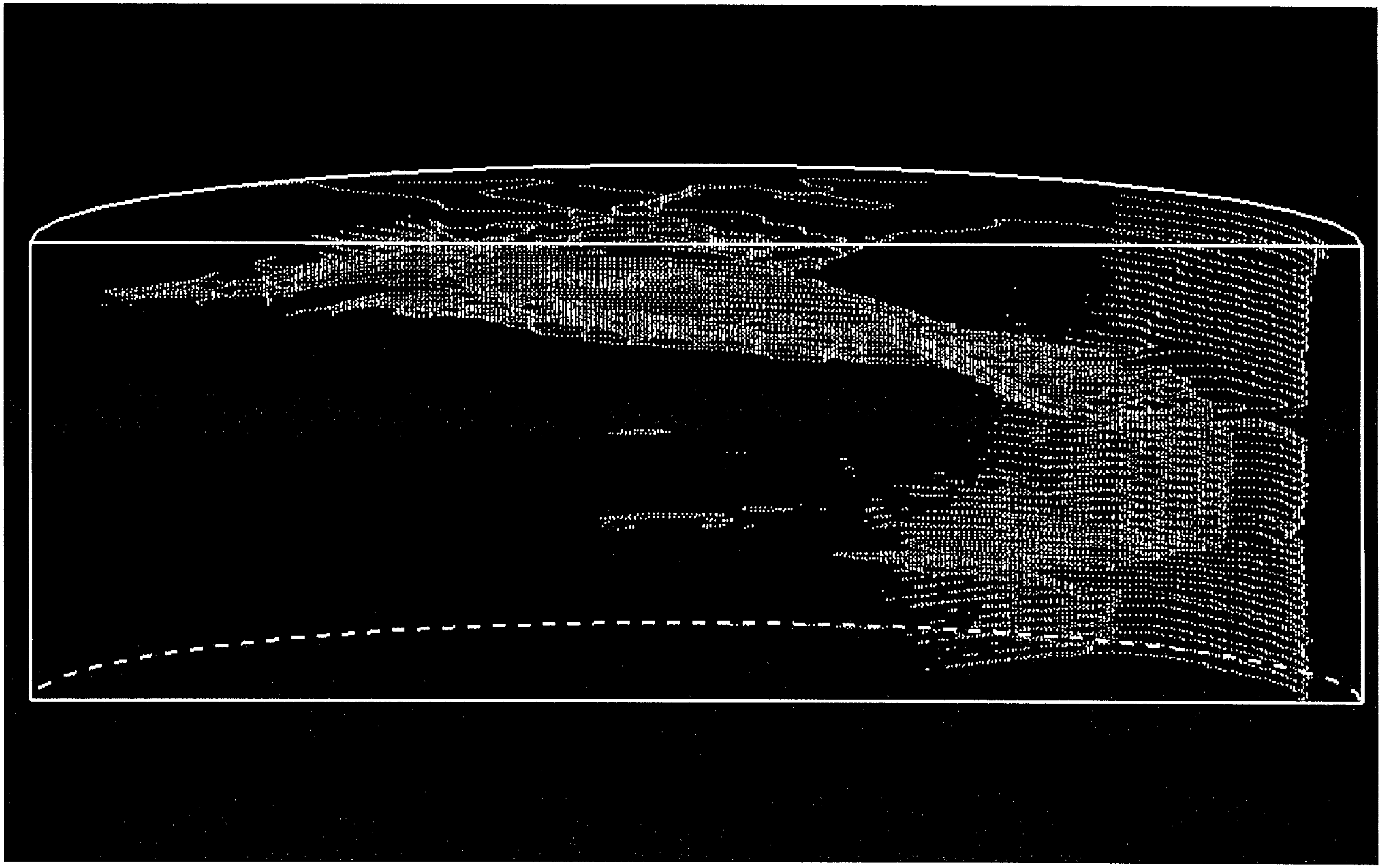

Figure B-17. 80° rotation about X-axis.

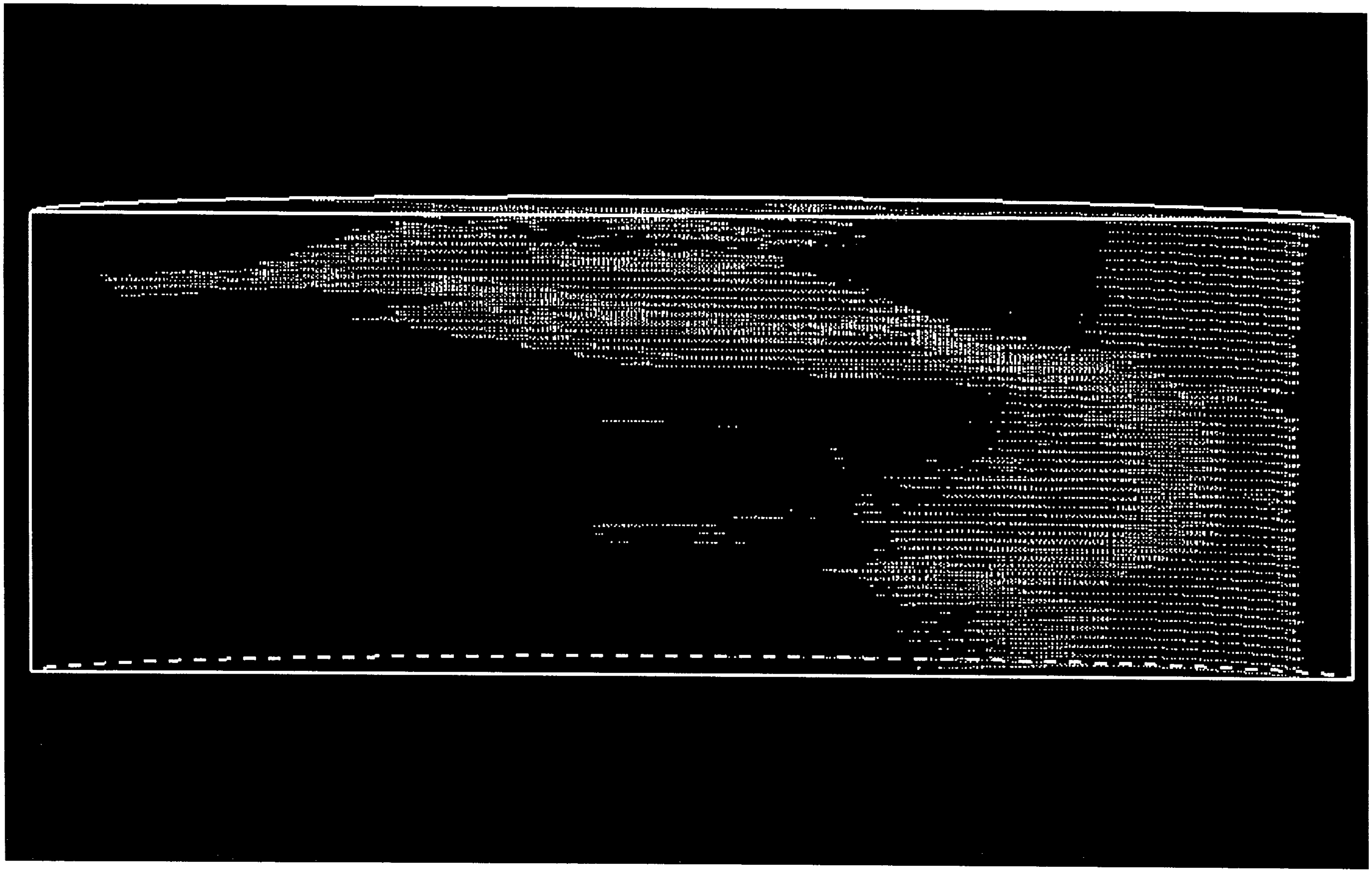

Figure B-18. 85° rotation about X-axis.

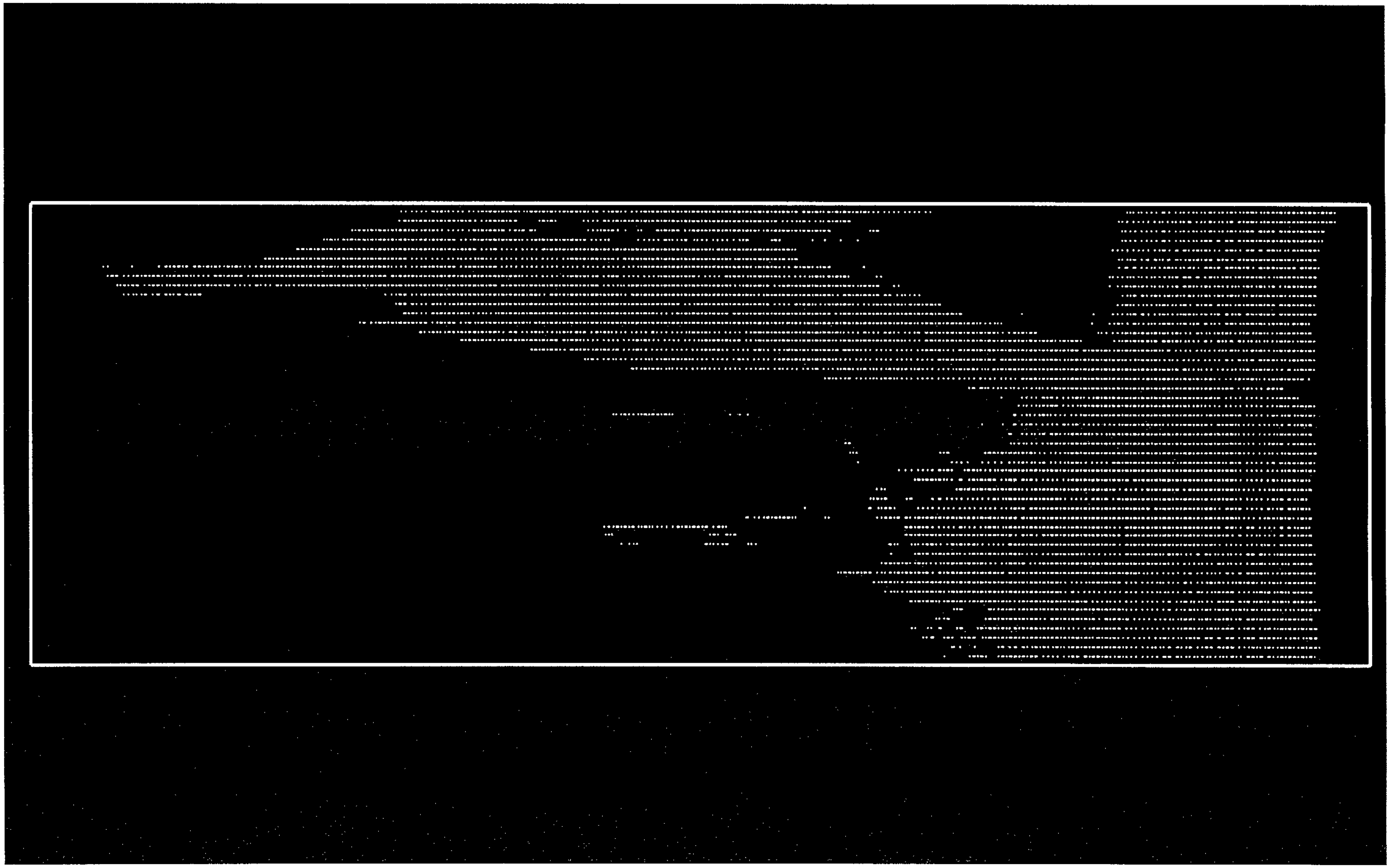

Figure B-19. 90° rotation about X-axis.

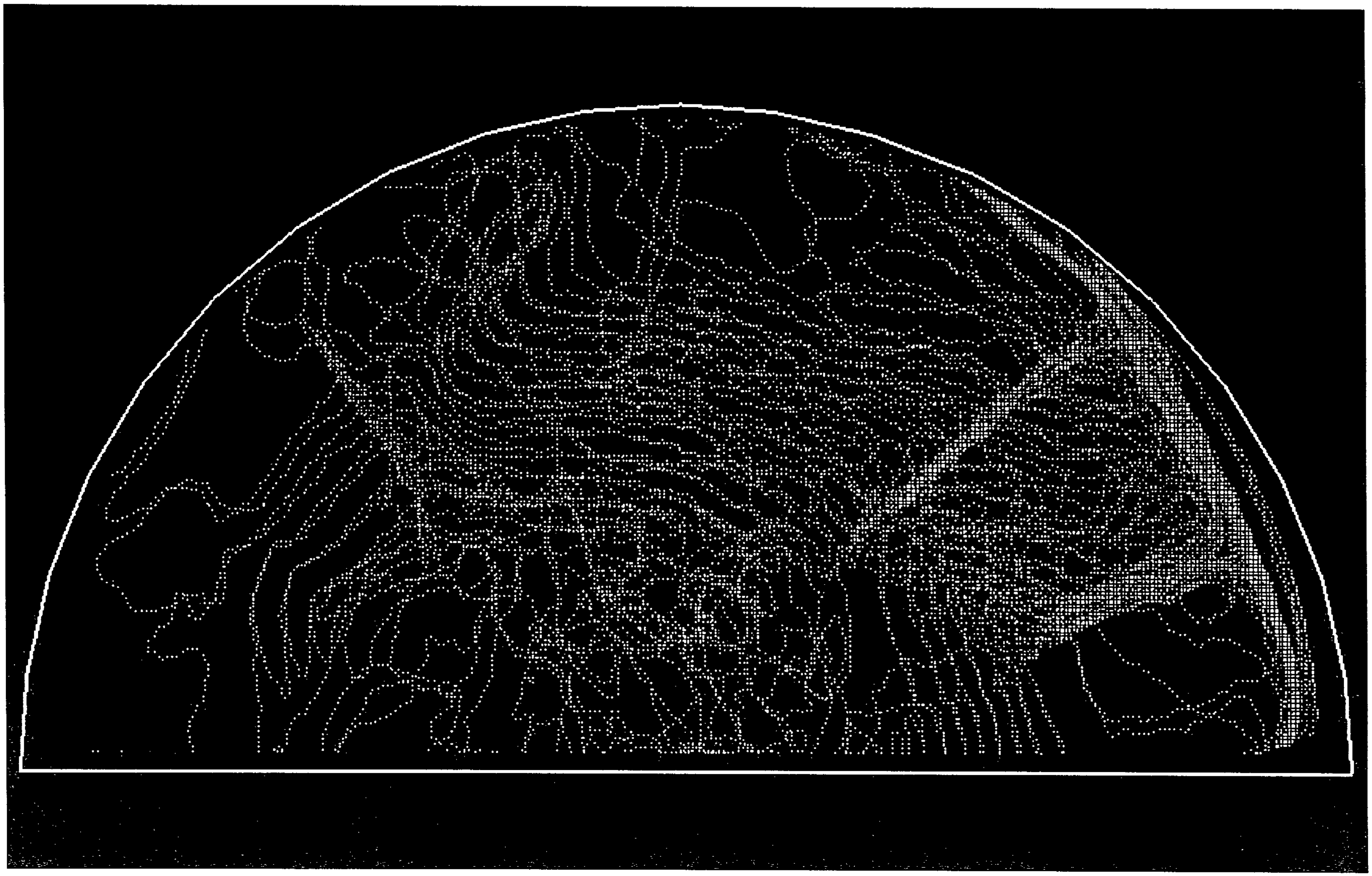

Figure B-20. 0° rotation about Y-axis.

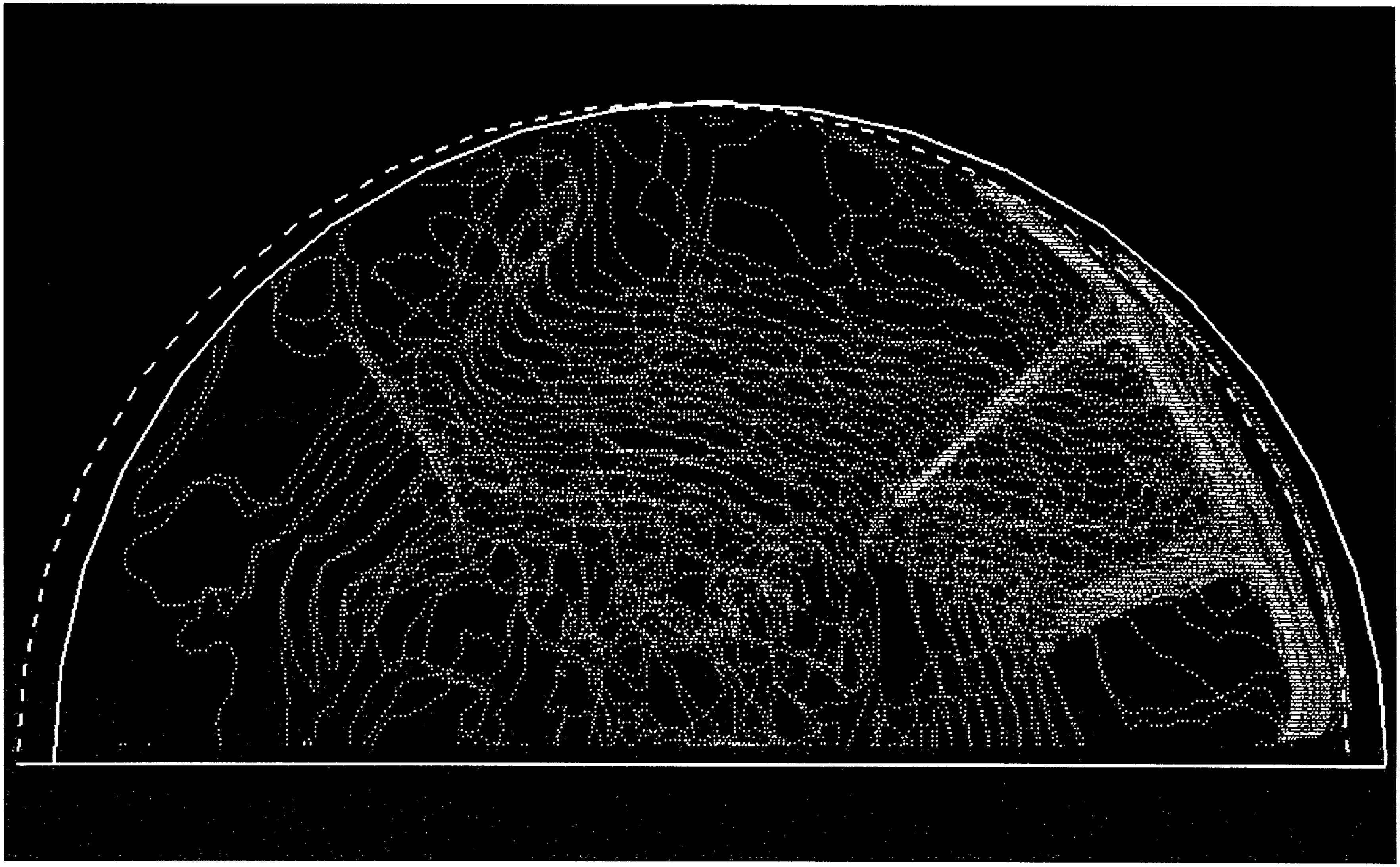

Figure B-21. 4.5° rotation about Y-axis.

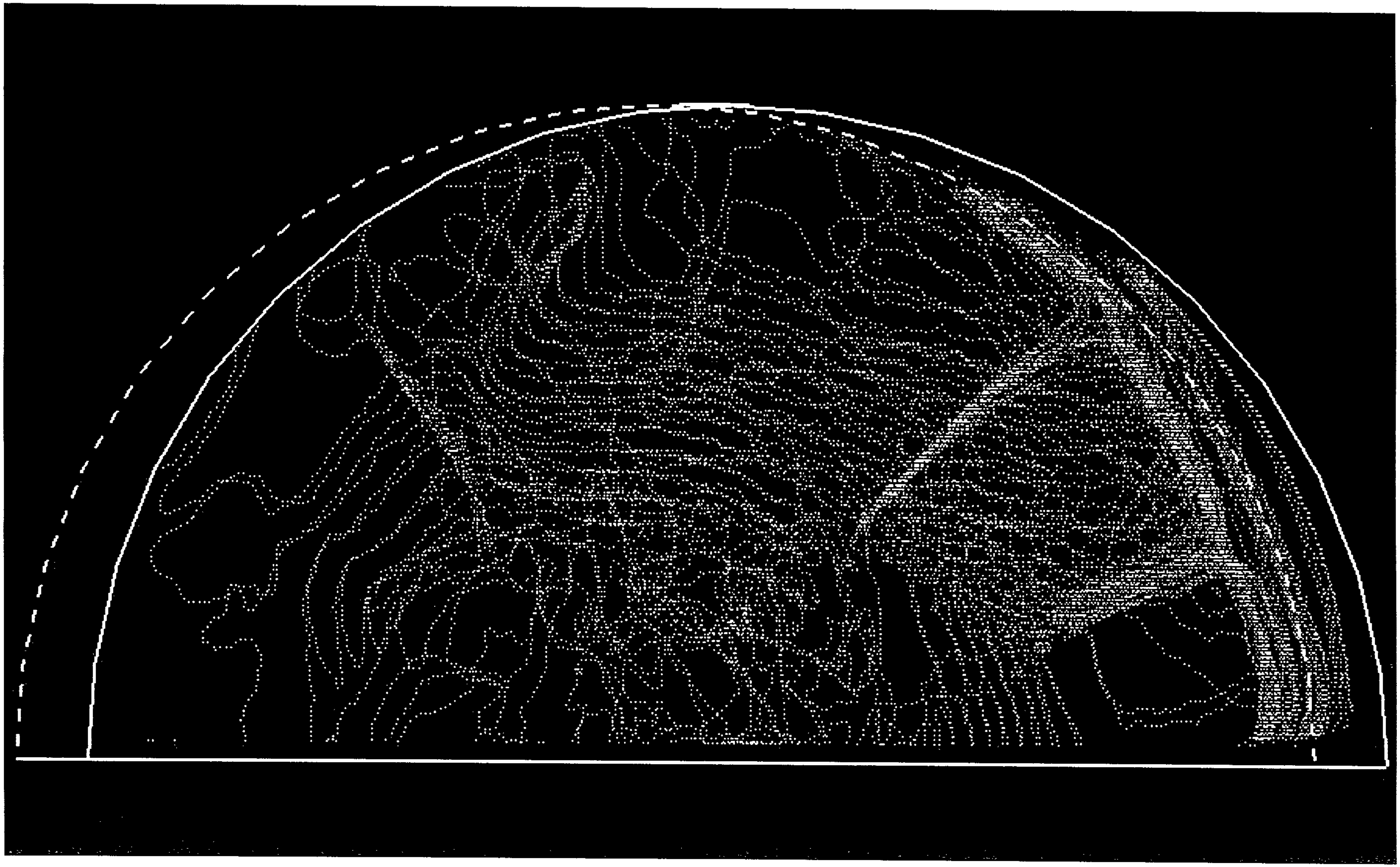

Figure B-22. 9° rotation about Y-axis.

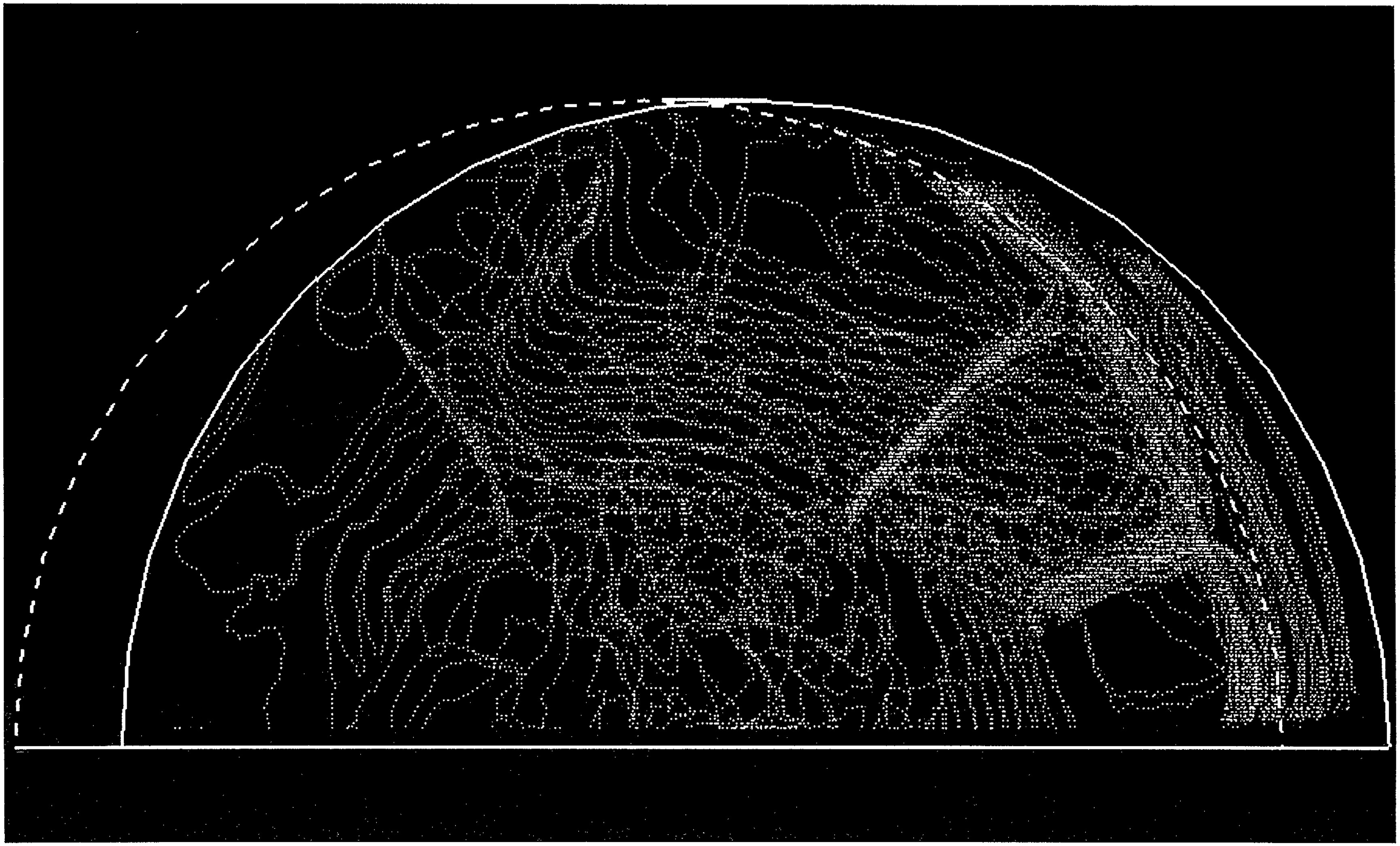

Figure B-23. 13.5° rotation about Y-axis.

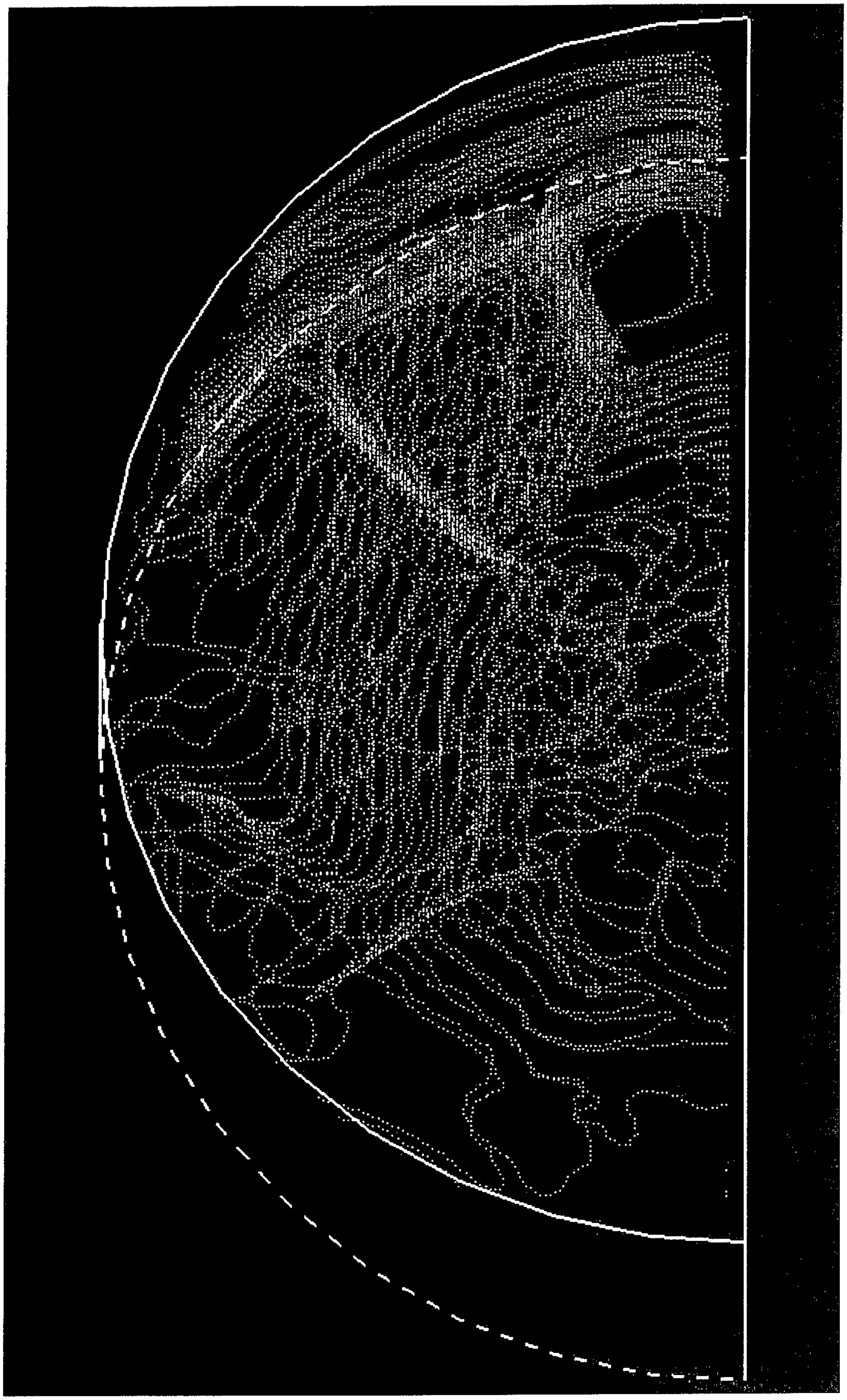

Figure B-24. 18° rotation about Y-axis.

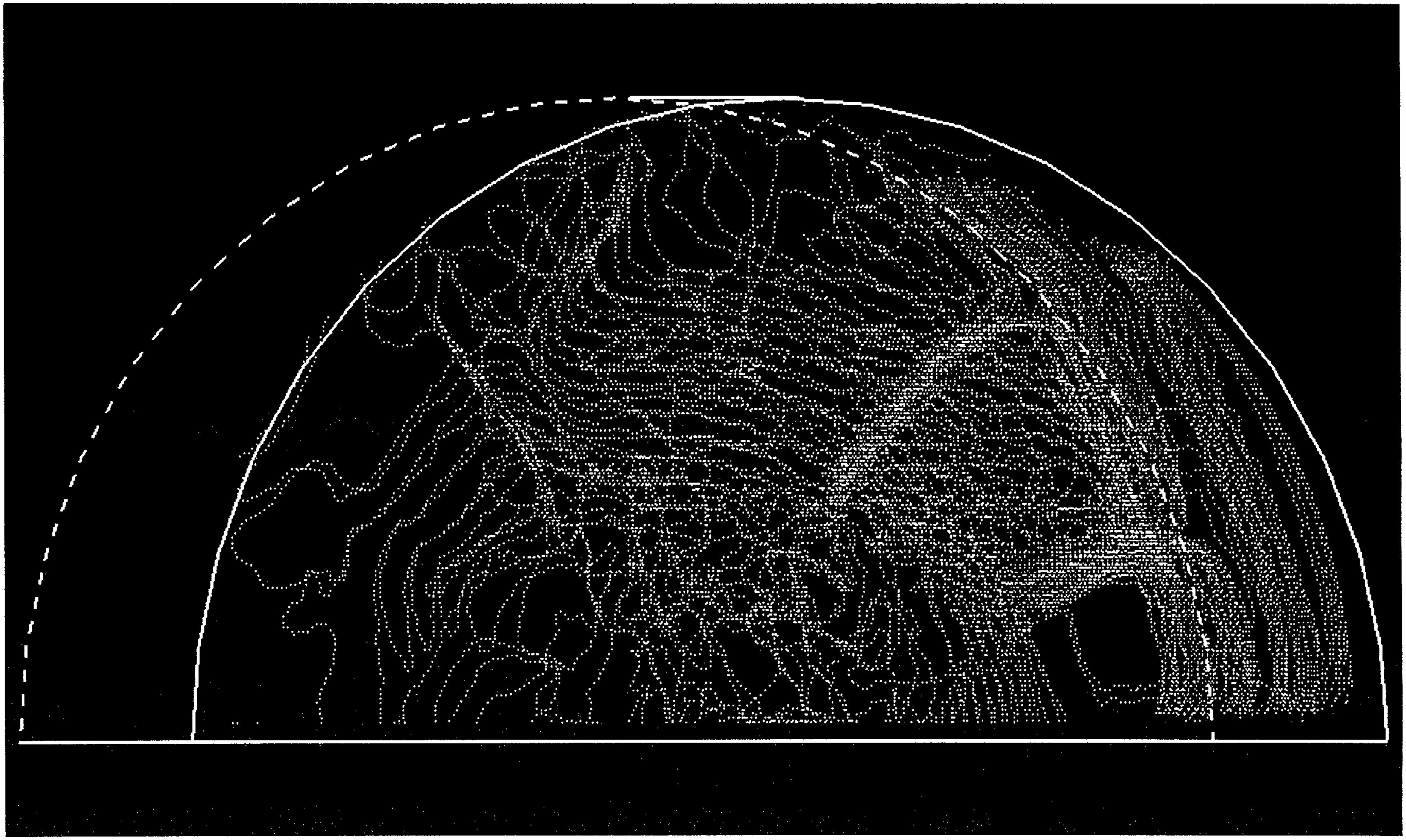

Figure B-25. 22.5° rotation about Y-axis.

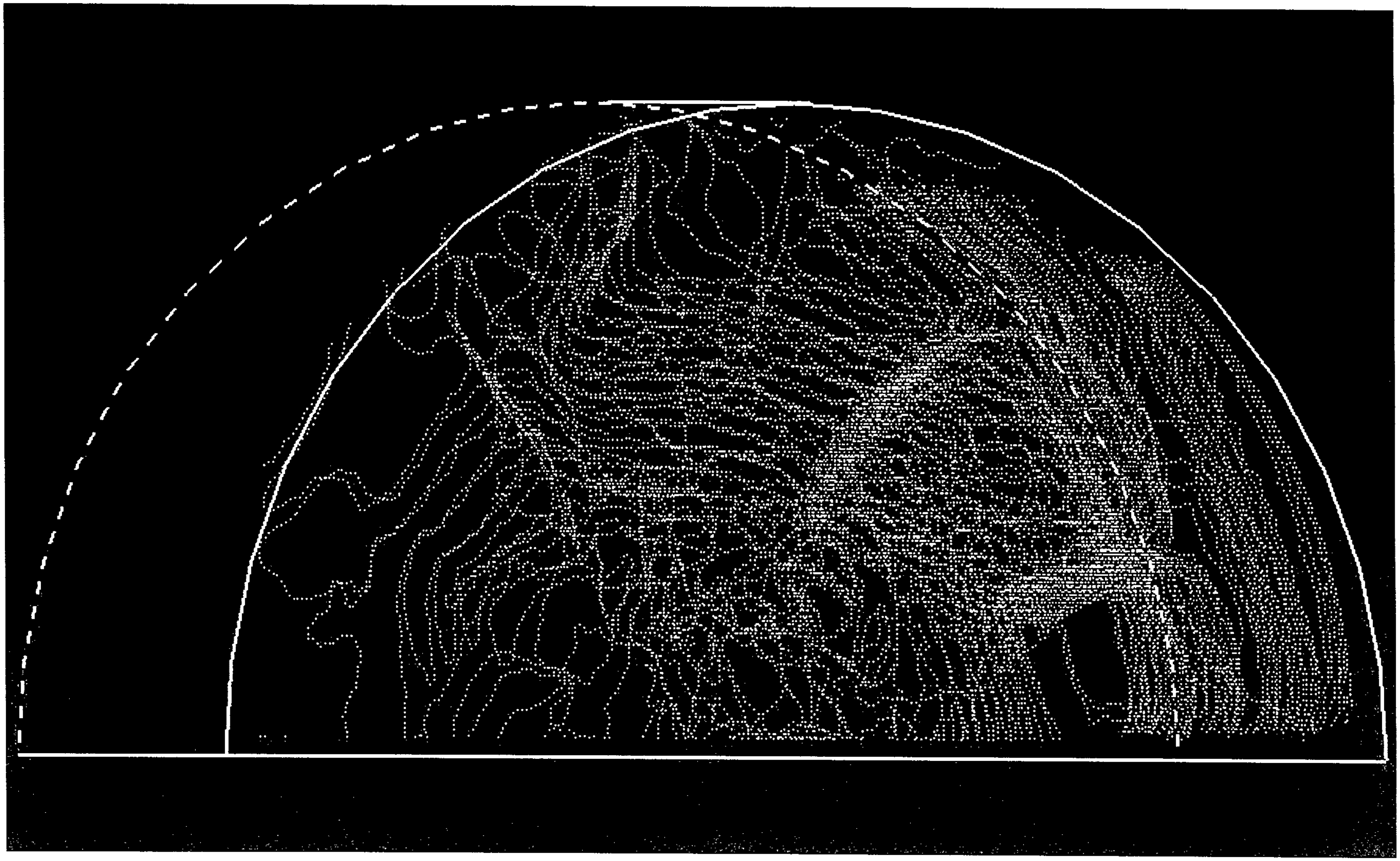

Figure B-26. 27° rotation about Y-axis.

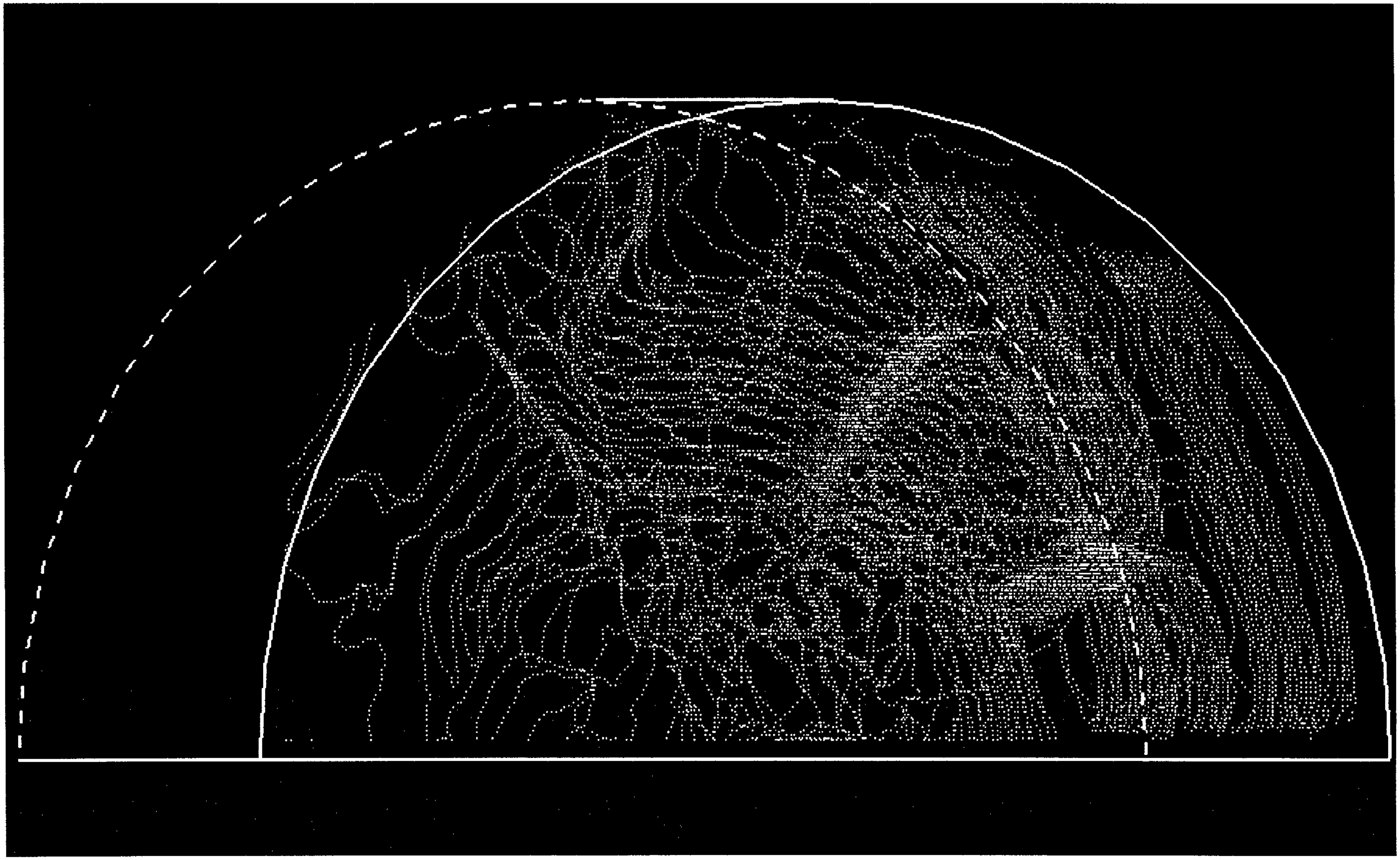

Figure B-27. 31.5° rotation about Y-axis .

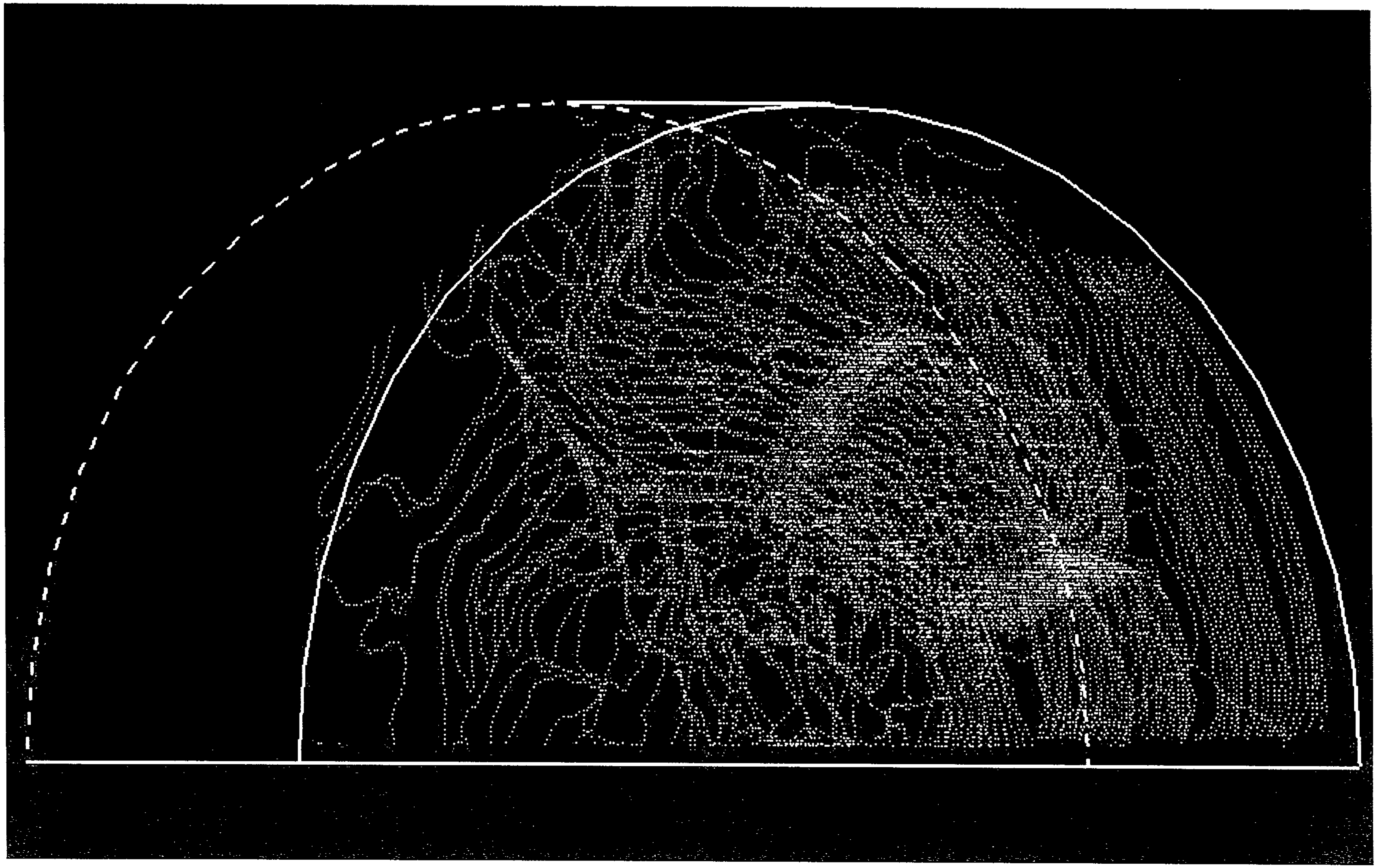

Figure B-28. 36° rotation about Y-axis.

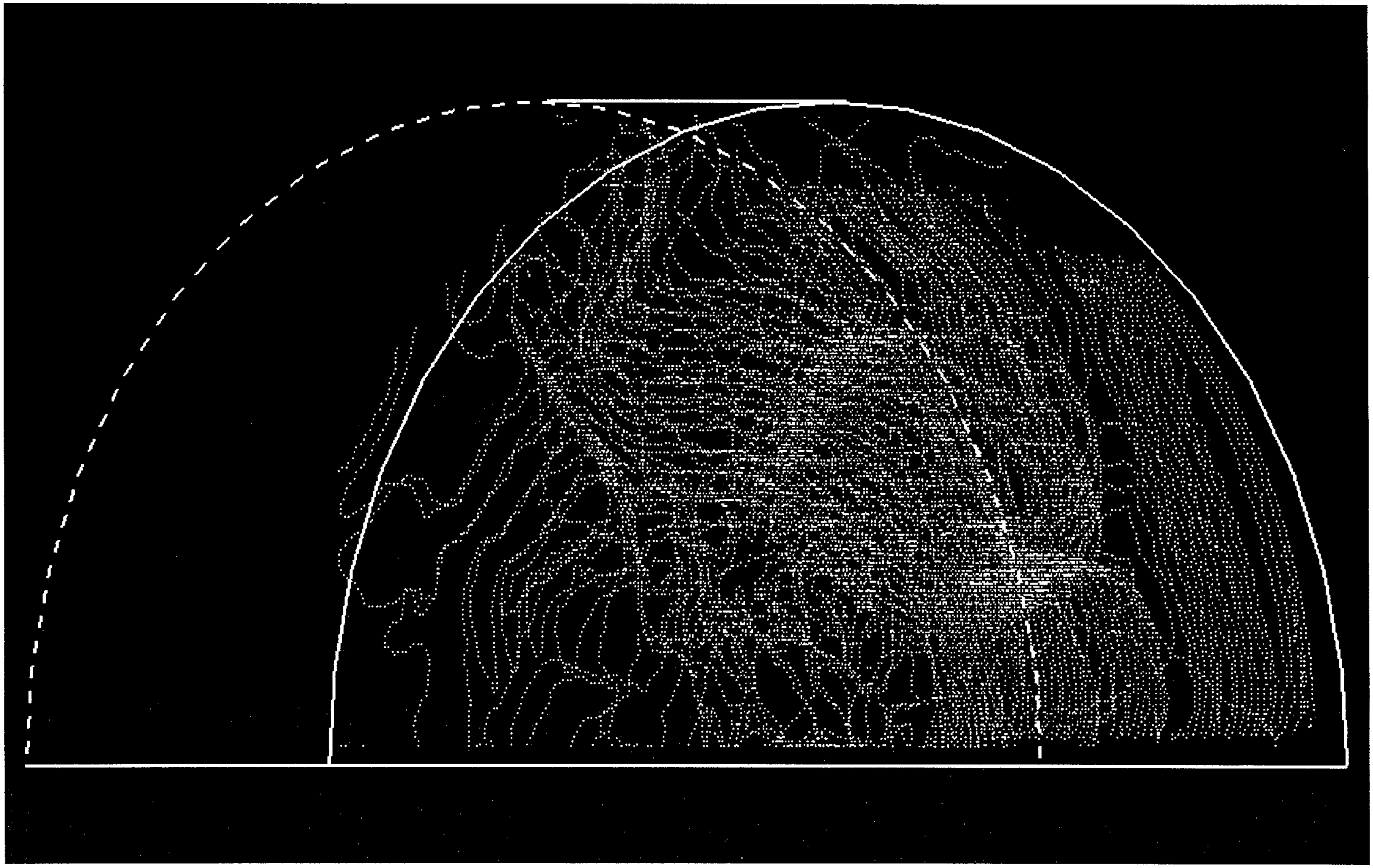

Figure B-29. 40.5° rotation about Y-axis.

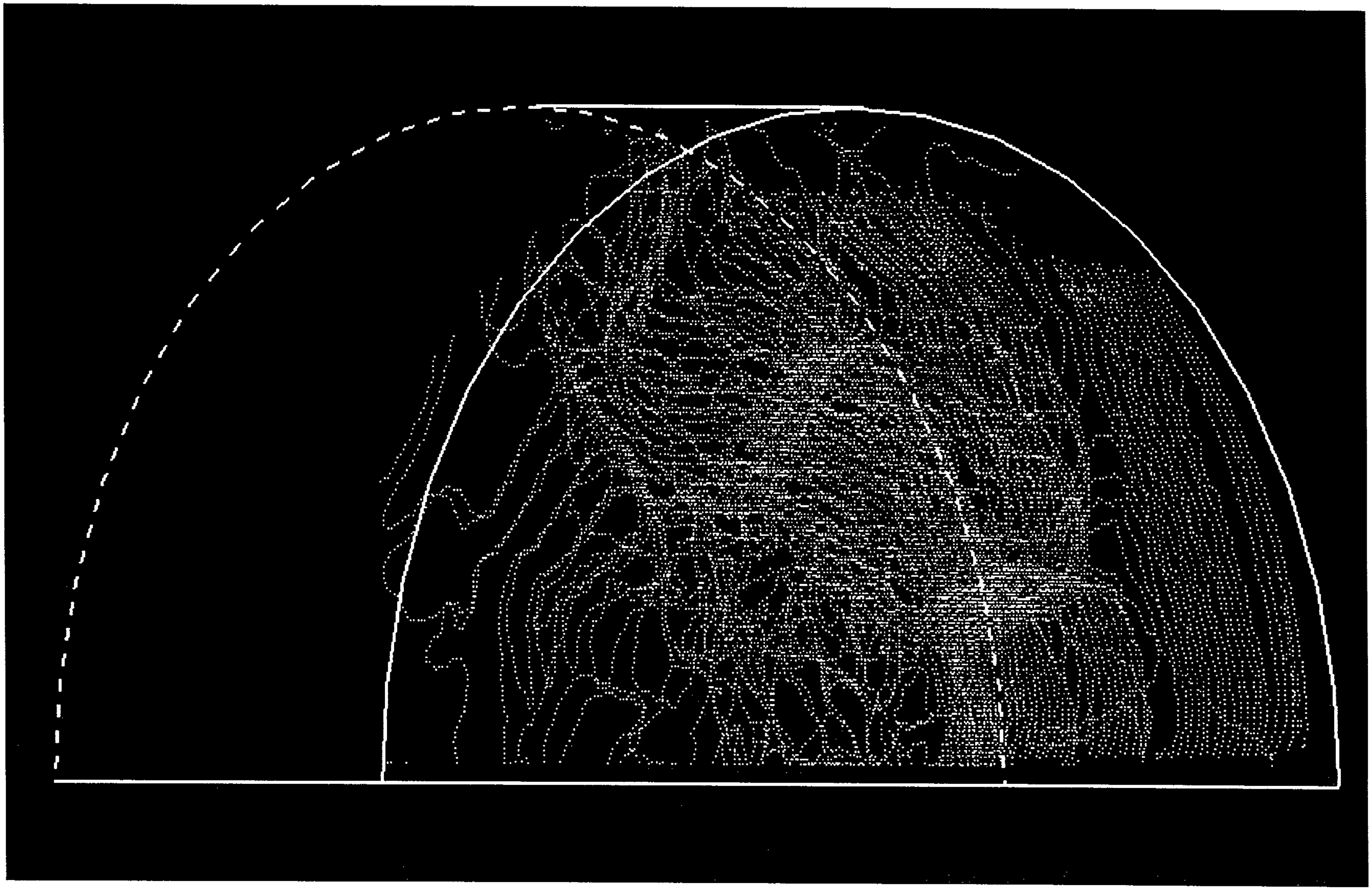

Figure B-30. 45° rotation about Y-axis.

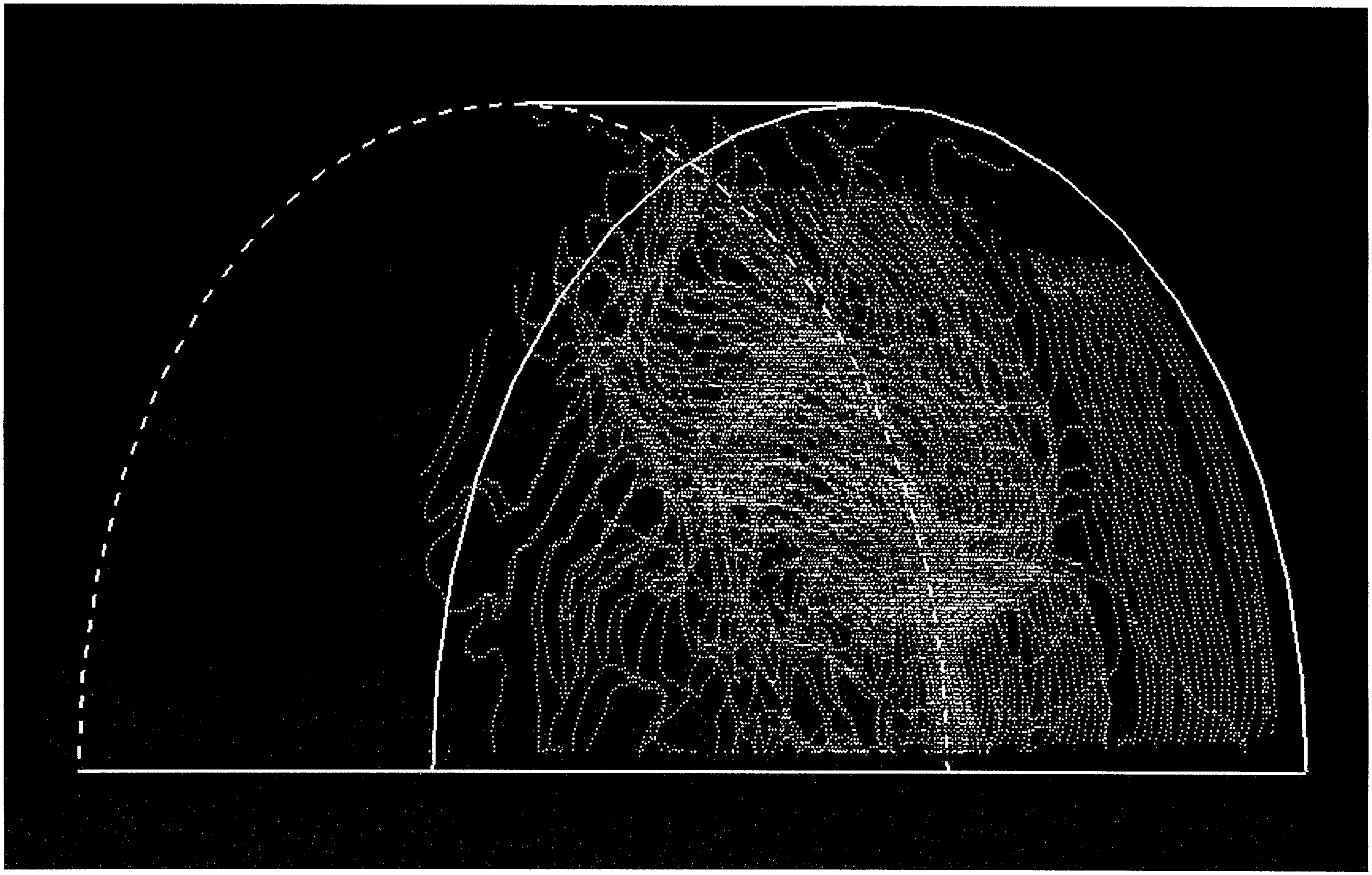

Figure B-31. 49.5° rotation about Y-axis.

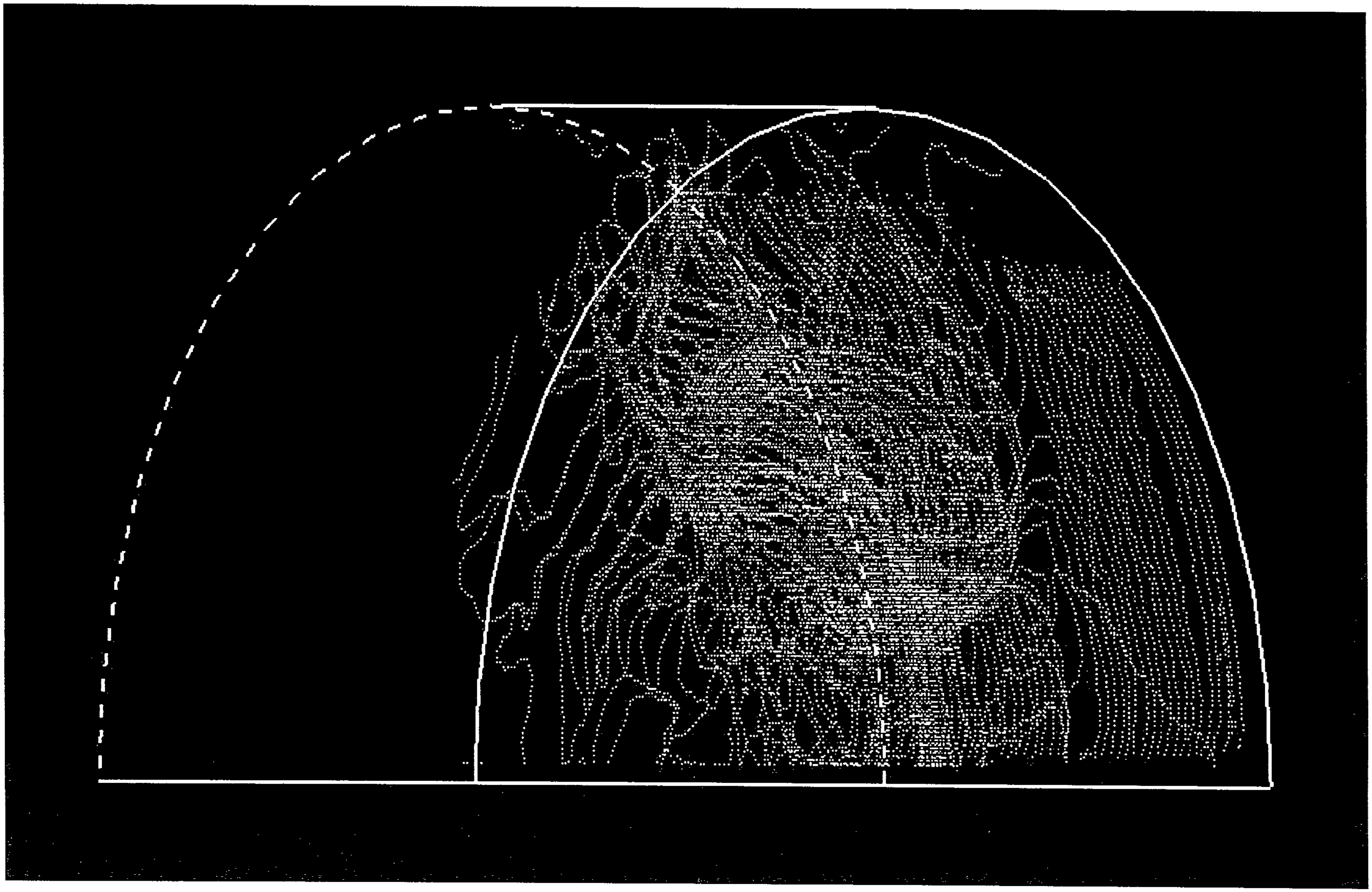

Figure B-32. 54° rotation about Y-axis.

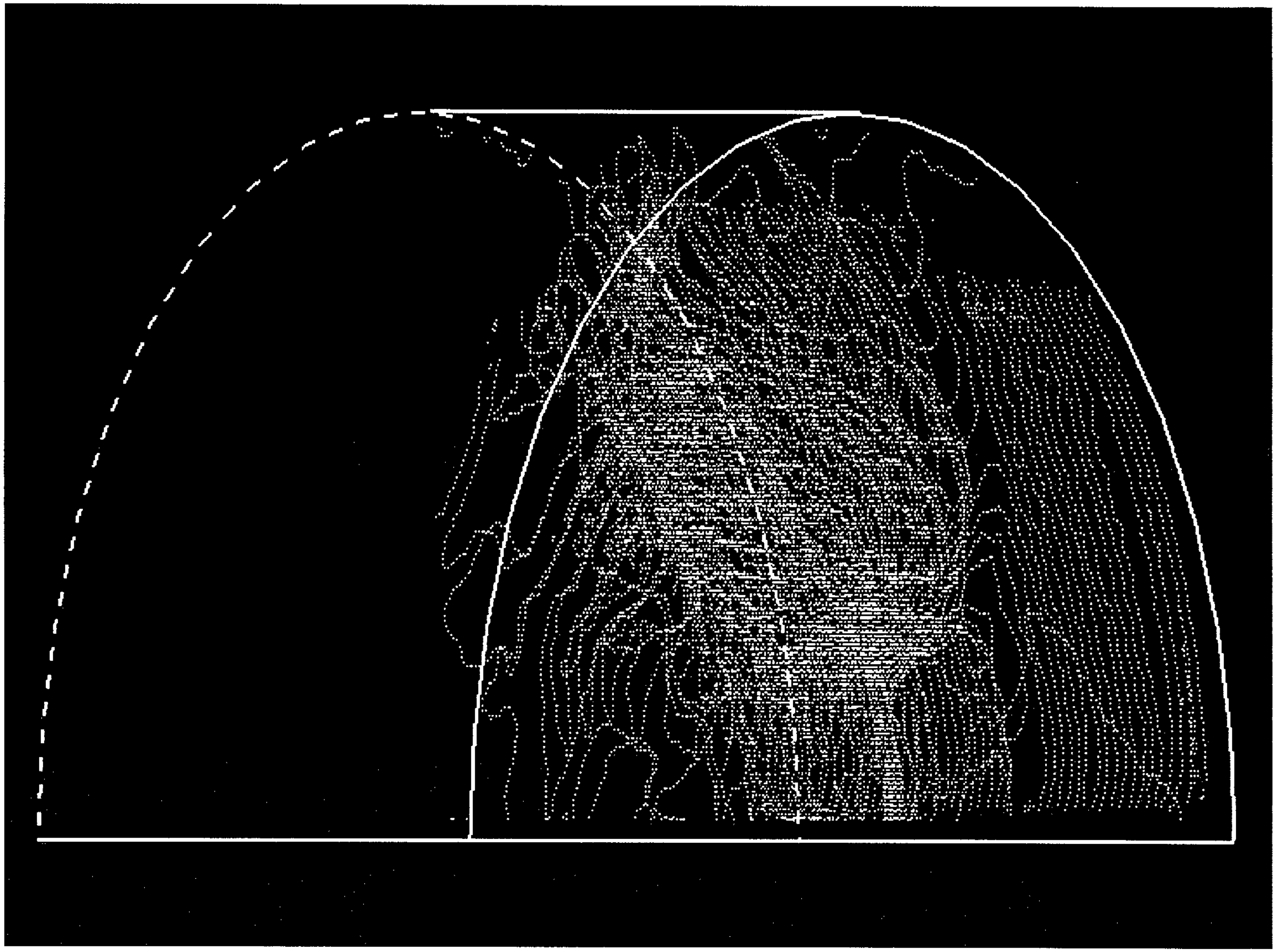

Figure B-33. 58.5° rotation about Y-axis.

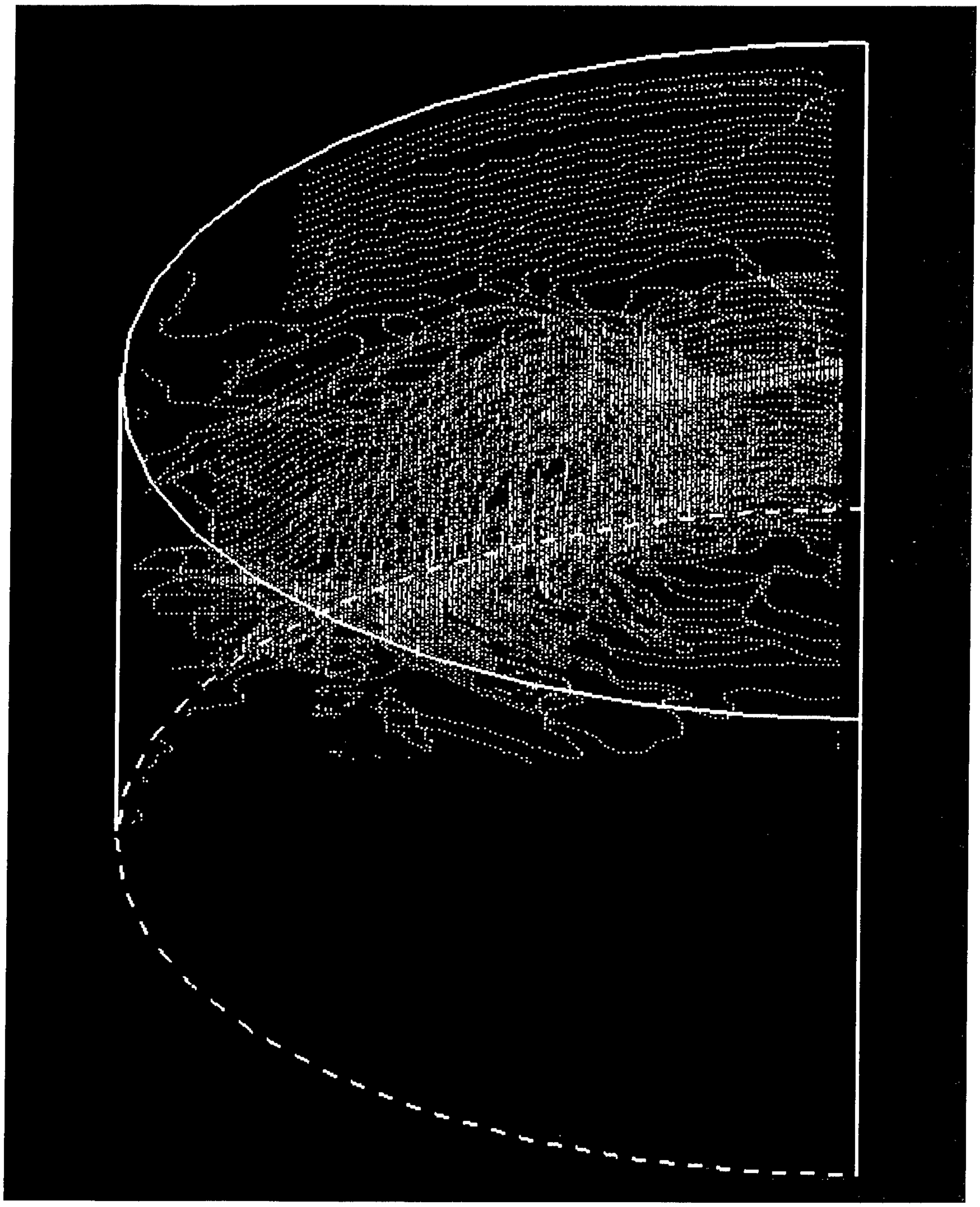

Figure B-34. 63° rotation about Y-axis.

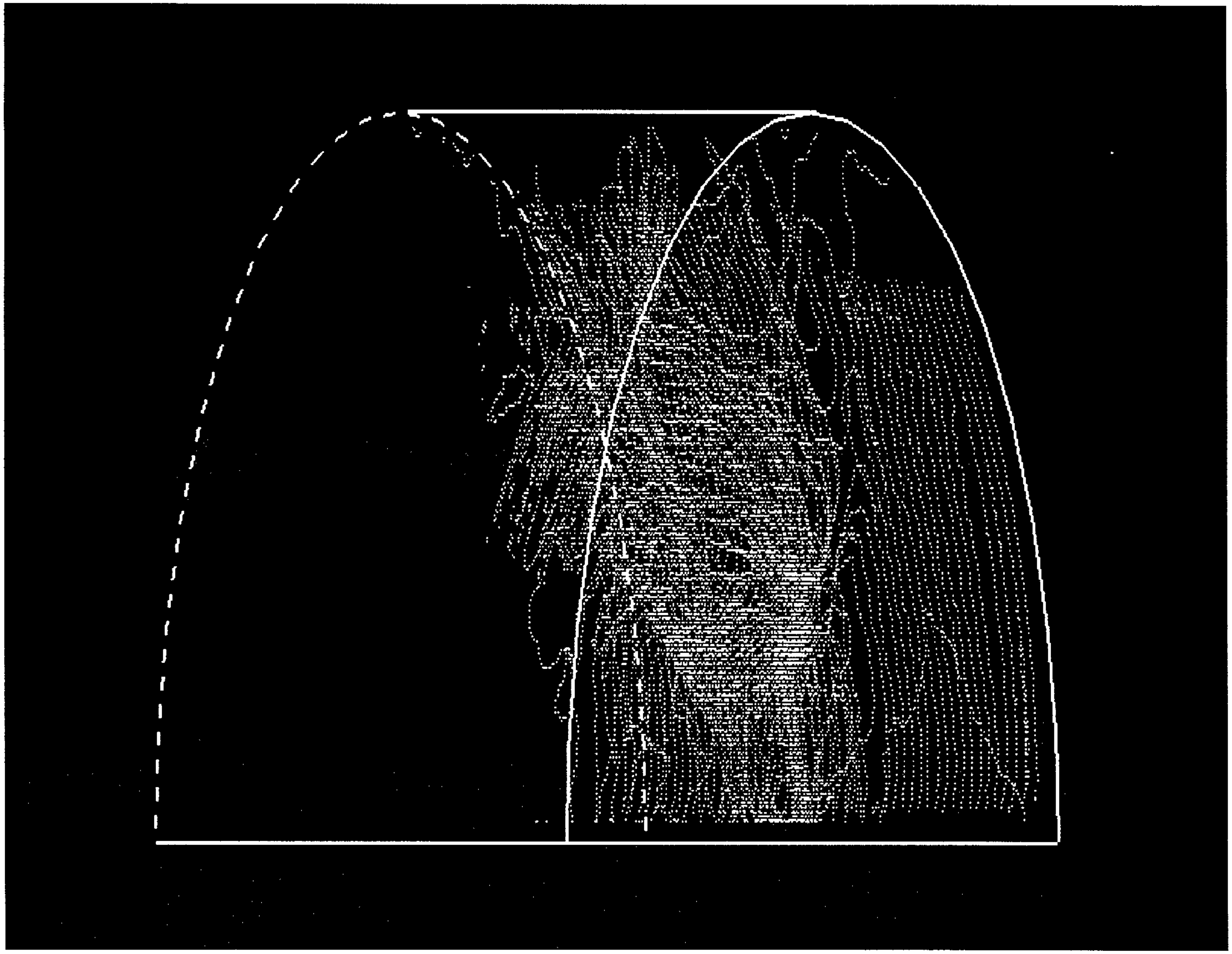

Figure B-35. 67.5° rotation about Y-axis.

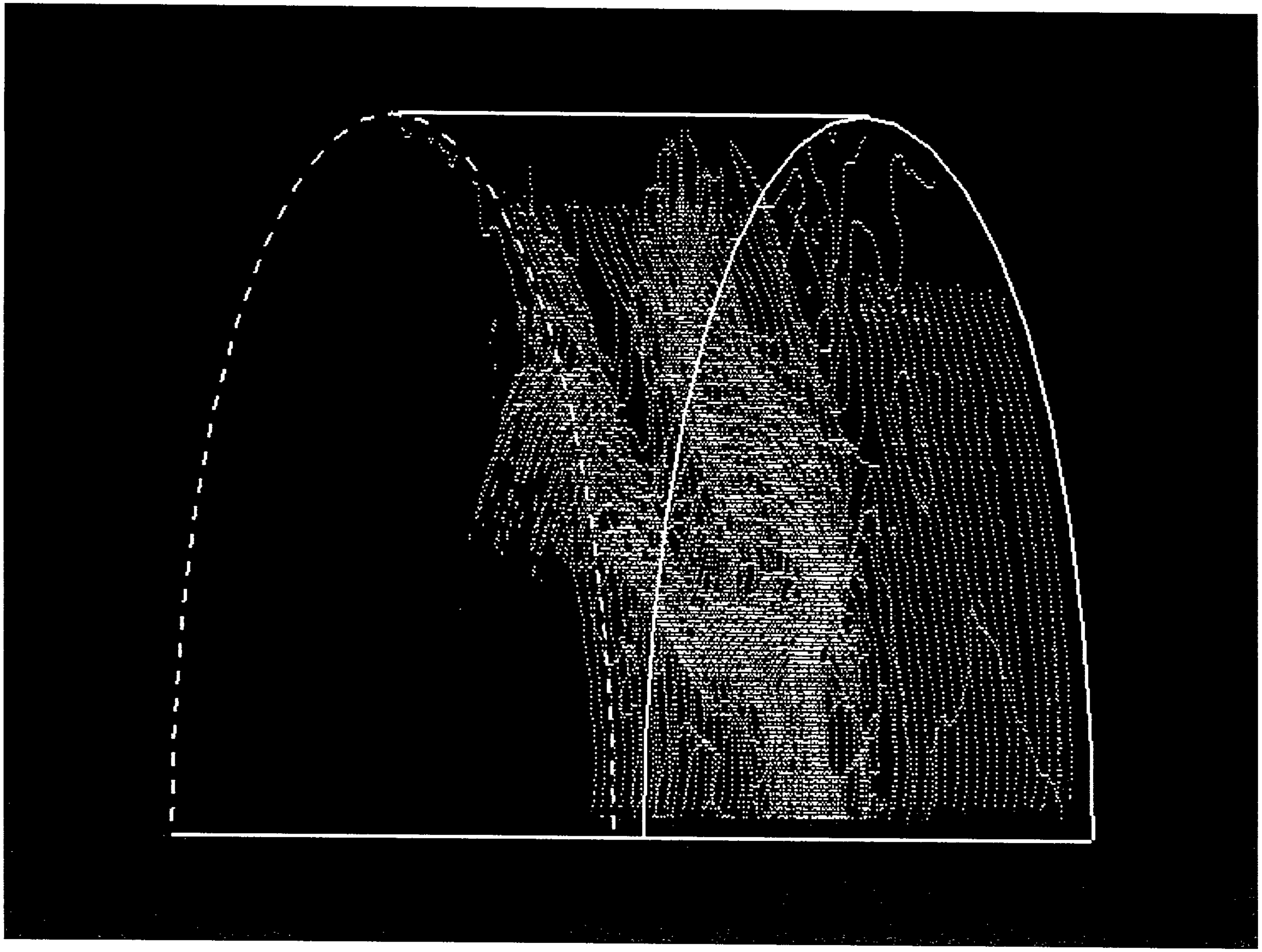

Figure B-36. 72° rotation about Y-axis.

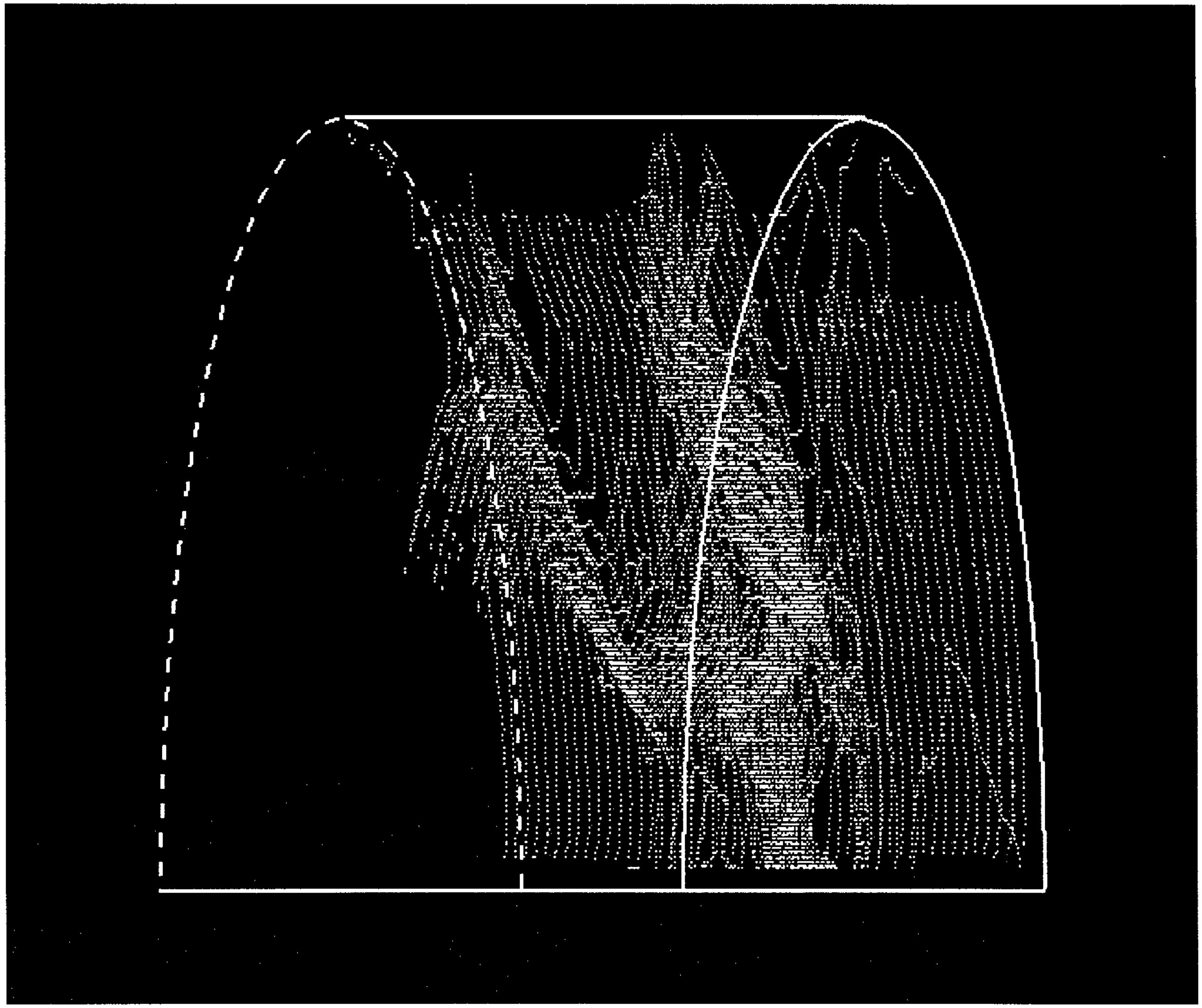

Figure B-37. 76.5° rotation about Y-axis.

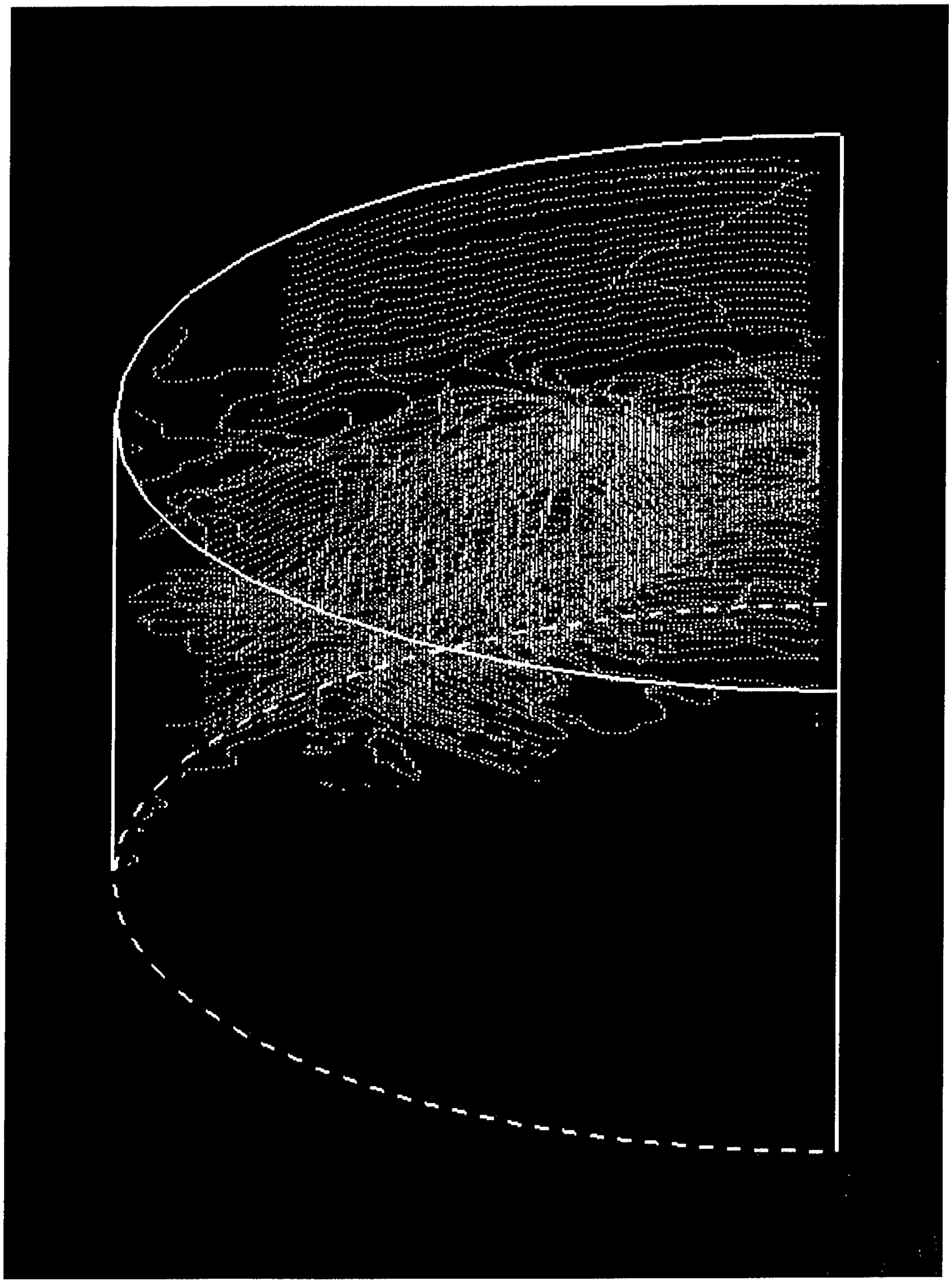

Figure B-38. 81° rotation about Y-axis.

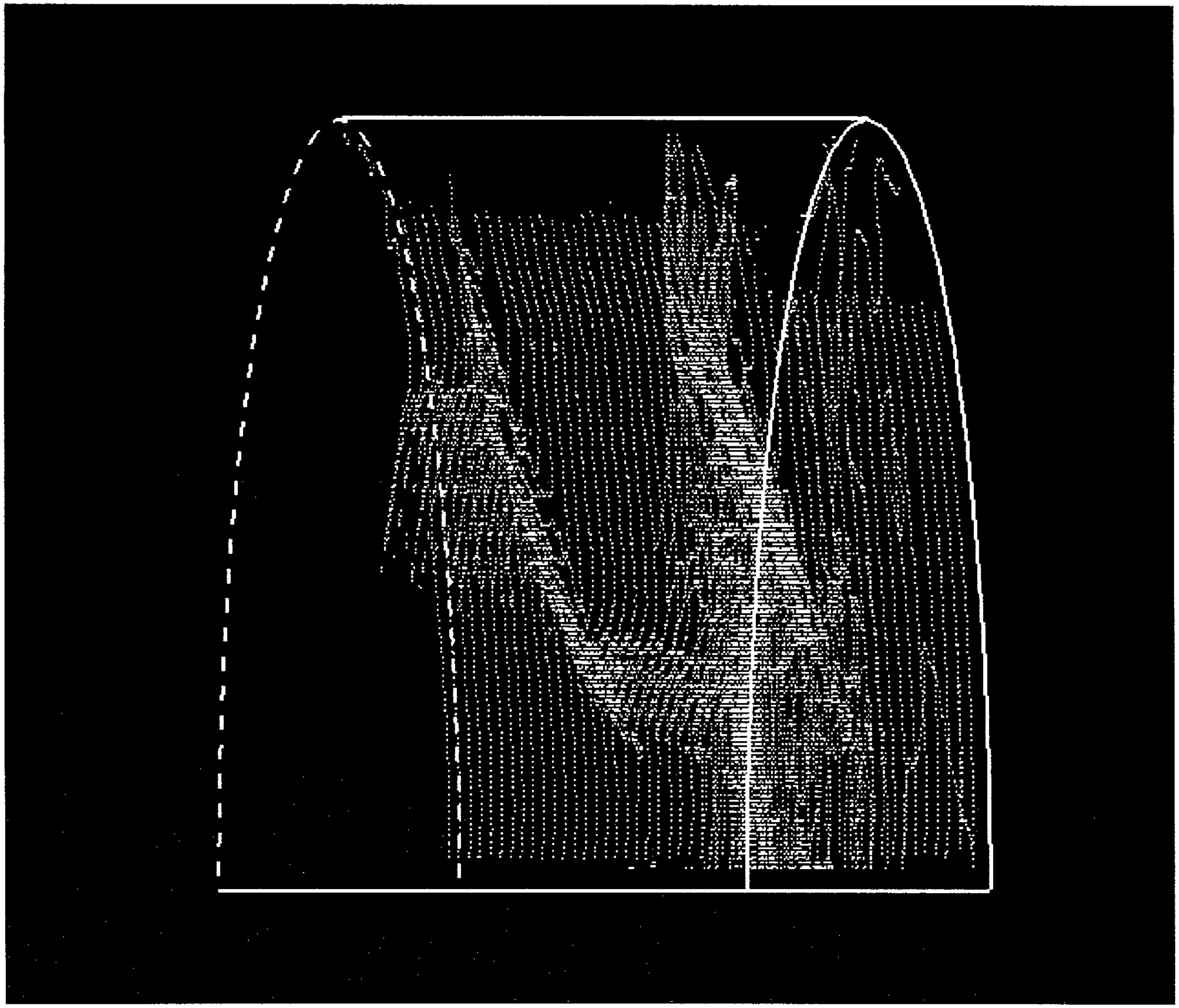

Figure B-39. 85.5° rotation about Y-axis.

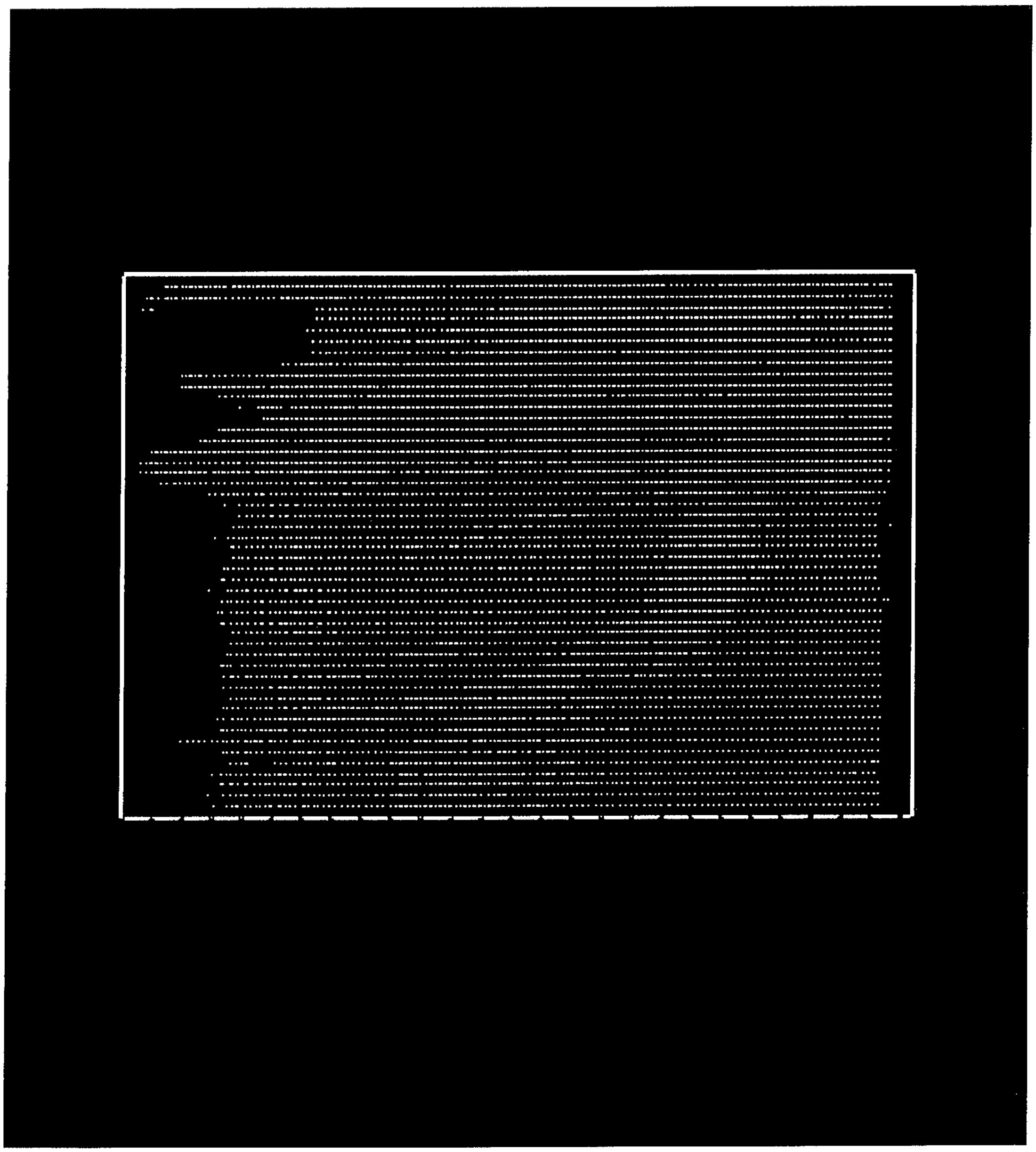

Figure B-40. 90° rotation about Y-axis.

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13. ABSTRACT *(Maximum 200 words)*

This study was initiated to demonstrate the feasibility of applying the state-of-the-art nondestructive testing methodology known as x-ray computed tomography (CT) to a ballistic damage assessment. Specifically desired is the capture, digitization, and display, in both two-dimensional (2-D) and three-dimensional (3-D) formats, of the actual mesocracking damage created in bulk ceramic targets following an interface defeat or dwell ballistic impact experiment. Dwell involves the delay, and interface defeat involves the prevention, of penetration by a long rod penetrator into the ceramic. In each mechanism, the penetrator material contacting the ceramic front face flows laterally. These mechanisms occur at or near the impacted front surface of a highly confined armor ceramic material and may result in considerable subsurface or interior damage. This study also reports on the development of a new capability to graphically represent the full assemblage of networked interior mesocracks by an isolated 3-D point cloud or wireform model which aids significantly in the visualization and understanding of the entire mesocracking damage network. Practical limits of image spatial resolution with this technique (≈400 μm for large volume samples) preclude the nondestructive characterization of the detailed microcracking damage at this time.

14. SUBJECT TERMS
x-ray computed tomography, TiC ceramic, ballistic impact, interface defeat, mesocracking, 2-D and 3-D visualization, multiplanar reconstruction, 3-D solid reconstruction, 3-D point cloud, wireform model

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